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DIFFERENTIAL RESPONSES OF SOYBEAN VARIETIES TO APPLICATION OF PHOSPHORUS, POTASSIUM AND CALCIUM CARBONATE MATERIALS WITH RESPECT TO LEAF COMPOSITION AND YIELD

by

Cornelis Jacobus de Mooy

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Dean of Graduate College

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TABLE OF CONTENTS

I. INTRODUCTION

Soybean yield responses to phosphorus and potassium fertilizers have the reputation of being small and inconsistent, unless the soil tests low to very low with respect to these elements. Consequently, the fertilization of soybeans is commonly left to the residual effect of fertilization of other members in the crop rotation, corn, small grains and meadow. The general objective of the present study was to analyze the nature of soybean responses to fertilization and to investigate means by which the magnitude and consistency of such responses may be improved. Responses measured in terms of changing chemical composition of the leaves of the plant, differences in growth at various stages of development and differences in yield of soybeans all are of importance and contribute towards understanding of soybean plant behavior and the ultimate goal of higher or more efficient soybean production. Several possible approaches were considered and incorporated in the experimental plans.

New varieties may be scrutinized for promising characteristics. Previous concepts were based on experience with a number of commercial varieties originating from a rather restricted and partly common parentage. The original selection of these varieties was largely based on high yielding ability and consistency of high yields at many locations. Varieties highly responsive to fertilizers in terms of chemical composition may have been eliminated accidentally on grounds of other, undesirable, properties since tissue analyses were not employed at the time. Also, the number of varieties inspected was a very small fraction of the number of soybean varieties grown in various parts of the world. Even when imposing the restriction of being adapted to the photo-periodic conditions prevailing at the latitude of 40°, 355 suitable soybean varieties and lines remain from the Plant Introduction collection of the USDA. These were grown in the field at Ames with two replications. Fourty eight of them were selected on the basis of extremes in chemical composition and yield. They were grown in the following year at two levels of fertility and in two replications. Two introduced lines from the first year and three from the second year, far apart in chemical composition and yield, were selected for further testing in pot experiments.

Another aspect of the problem was that higher rates of fertilization might be required to show consistent trends where the responses per unit fertilizer are small. Also, if interaction effects occur, a response to one nutrient may not be found until another nutrient is present in high amount.

Thirdly, the need for nutrients other than phosphorus and potassium could cause inconsistent responses. A third element, calcium, was therefore included as a variable in most experiments to cover the possibility of essential interaction effects.

Differential responses have been shown to exist in corn (Jones, 1960). Jones concluded that some inbred lines have a lower K requirement than others and also are more sensitive to high K levels. Since the soybean lines employed represented extremes in the range of yield and chemical composition, failure to detect differential responses among them would suggest that no such differences may occur amongst any lines, provided the experiments were sufficiently sensitive to show the desired effects if they existed. Pot trials were chosen for this study since they allow greater precision and control of growth factors than field experiments.

Field experiments were employed to study the comparative behavior of four commercially grown varieties. Since several varieties and three nutrient variables were involved at 5 to 9 rates of application it was essential to restrict the number of pots and field plots to a minimum. Composite designs and statistical methods perfected in the last 10 to 15 years greatly facilitated the trials and the tests on differential responses.

It was attempted to meet the general objective of establishing large and consistent fertilizer responses in soybeans by the various means outlined. Since some varieties are likely to be more responsive than others a good possibility to discover large responses would lie in testing for differential effects. Several varieties were accommodated in every experiment and grown side by side to study this aspect.

II. EXPERIMENTAL PLANS AND PROCEDURES

A. Soybean Varieties and Plant Introductions Used in the Investigation

1. Pot experiments

Two pot experiments were conducted to study the response of some introduced lines of soybeans to P, K and Ca application and to determine the magnitude and statistical significance of differential responses among them. The first trial was carried out during the early summer of 1962 and the second trial during the summer of 1963.

Five introduced lines were used in these experiments:

P. I. 60296-1
P. I. 200479
P. I. 88805-2
P. I. 89005-4
P. I. 84957

These lines will be referred to hereafter as Entry 1, 2, 3, 4 and 5 in this order. Entry 1 was selected from the 1962 field trial of 48 lines for its high P content of the leaves (0.40%) and high yield (40 bushels per acre). Entry 2 was chosen for its low P content (0.30%) and low yield (27.7 bushels per acre) to provide a contrast to Entry 1. Entry 3 was chosen for its high K content (1.85%) in the leaves.

Using Tukey's Q test (Snedecor, 1956, p. 251), which is a most conservative test, Entry 1 yielded significantly higher than Entry 2. The entries 1 and 3 were significantly higher in percent P than Entry 2 and Entry 3 was significantly higher in percent K than Entries 1 and 2.

The Entries 4 and 5 were isolated from the 1961 plantation of 355 varieties and lines. Entry 4 was selected for high P and K content of the leaves (0.45% P and 1.47% K), in contrast to Entry 5 which showed a low P and K content of the leaves (0.27% and 0.87%, respectively).

2. Field experiments

Differences in response to fertilization among commercially grown varieties were studied in two field experiments conducted during the summer of 1961. Four varieties were compared: Chippewa, Blackhawk, Harosoy and Hawkeye. In the following discussion these will be referred to as Ch, Bl, Hr and Hk.

B. Experimental Design

The objectives of this study entailed the use of two to four varieties, three nutrient variables each at five to nine levels, all of which were to be replicated twice in every experiment. If all treatment combinations of a full factorial had to be allocated to large-sized plots for repeated sampling and yield test the field experiments would tend to become too extensive to fit into any section of uniform soil. Likewise, the pot trials would be too laborious to handle, particularly since the number of pots to be provided is multiplied by the number of stages of development at which sampling is intended.

The development of composite designs since 1951, when Box and Wilson (1951) proposed their new designs for quadratic surfaces, had made it possible to reduce the number of experimental units considerably without loss of information on those effects which are of interest. Use of these designs in agronomic research has led to some adaptations. Each of the three designs used in this study has a control plot as part of the set of treatment combinations. The one used in the two pot experiments accommodates three nutrient variables at five levels. The coded treatment combinations used are given in Table 1.

Table 1. Treatment combinations for the pot experiments

Treatment number	Levels[a] of		
	P	K	Ca
1	1	1	1
2	1	1	3
3	1	3	1
4	1	3	3
5	3	1	1
6	3	1	3
7	3	3	1
8	3	3	3
9	2	2	2
10	0	2	2
11	4	2	2
12	2	0	2
13	2	4	2
14	2	2	0
15	2	2	4
16	0	0	4
17	0	4	0
18	0	4	4
19	4	0	0
20	4	0	4
21	4	4	0
22	4	4	4
23	0	0	0

[a]A unit of P is 200 pp2m P in pot experiment 1962. A unit of P is 150 pp2m P in pot experiment 1963. A unit of K is 200 pp2m K. A unit of Ca is 1000 pp2m Ca.

The designs employed for the field trials have two or three variables at nine levels each and are given in Table 2.

P, K and Ca were used as variables in the Howard County experiment, while the variables in the Carrington-Clyde experiment were P and K.

The experimental design of the pot experiments in the proper sense of the term was randomized blocks, while the field experiments were split-plot designs with two replications. Fertilizer treatments were randomly allocated to the whole plots and varieties were the subplots. The blocks were laid out so as to remove as much variation due to position on the slope as possible.

C. Field Technique and Laboratory Procedures

1. Pot experiments

A Clarion silt loam profile was stripped of surface soil to 6 inches depth for use in the pot experiments. The soil was screened and thoroughly mixed. Fertilizers were then added and the soil blended for ten minutes prior to filling of the pots. The soil profile was selected to have a medium K content, to be low but not very low in P and to be only slightly acid (P(dry) = 3.5 pp2m; K(moist) = 182 pp2m; pH = 6.20), since it was intended to establish effects and differential effects in the area of inconsistent responses.

Plastic-lined tin cans holding 5 lbs. of moist soil were used in the pot trial in 1962. A drain pipe was inserted at the bottom and bottles were used to collect and store drainage water until the soil dried out sufficiently to return the water to the can. This was done to

Table 2. Treatment combinations as levels[a] of P, K and Ca in the field experiments

Treatment number	Howard County P	Howard County K	Howard County Ca	Carrington-Clyde P	Carrington-Clyde K
1	3	3	3	3	3
2	5	3	3	5	3
3	3	5	3	3	5
4	5	5	3	5	5
5	3	3	5	2	2
6	5	3	5	6	2
7	3	5	5	2	6
8	5	5	5	6	6
9	2	2	2	0	0
10	6	2	2	8	0
11	2	6	2	0	8
12	6	6	2	8	8
13	2	2	6	4	4
14	6	2	6	0	4
15	2	6	6	8	4
16	6	6	6	4	0
17	0	0	0	4	8
18	8	0	0	1	4
19	0	8	0	7	4
20	8	8	0	4	1
21	0	0	8	4	7
22	8	0	8		
23	0	8	8		
24	8	8	8		
25	4	4	4		
26	0	4	4		
27	8	4	4		
28	4	0	4		
29	4	8	4		
30	4	4	0		
31	4	4	8		

[a]A unit of P is 50 lbs. of P per acre. A unit of K is 100 lbs. of K per acre. A unit of Ca is 250 lbs. of Ca per acre.

prevent loss of nutrients since the trials were kept outside under all weather conditions.

Large polyethylene containers, holding 28 lbs. of moist soil, were used in 1963. These were similarly drained and placed in rows in the field as shown in Plate 1. P was applied as monobasic calcium orthophosphate reagent grade chemical in 1962 in units of 200 pp2m P to a maximum of 800 pp2m. In 1963 concentrated superphosphate (20% P and powdered in a ball mill) was used as the source of P. The rates of P were reduced to three-fourths of that in the previous year because symptoms of P toxicity were very severe under high P treatments in 1962 and it was intended to grow the 1963 crop to maturity without loss of information.

Potassium sulfate was the source of K in both years and was applied in units of 200 pp2m K to a maximum of 800 pp2m.

Ca was added as reagent grade calcium carbonate in the first, and as barn lime (finely ground limestone) in the second year. A sample of barn lime was analyzed and found to contain 39.65% Ca and 0.23% Mg so that the material could be considered as pure calcium carbonate for the purpose. The rates were based on units of 1000 pp2m Ca to a maximum of 4000 pp2m Ca.

The 1962 trial was planted on June 10 with seed treated with Arasan to prevent fungus attack. The seed was inoculated with commercial inoculant applied as a slurry. The pots were adjusted to constant weight with silica sand and watered and weighed twice a day to a moisture content of 25.8%. Prior to the start of the experiment it was established

Plate 1. Layout of pot experiment 1963

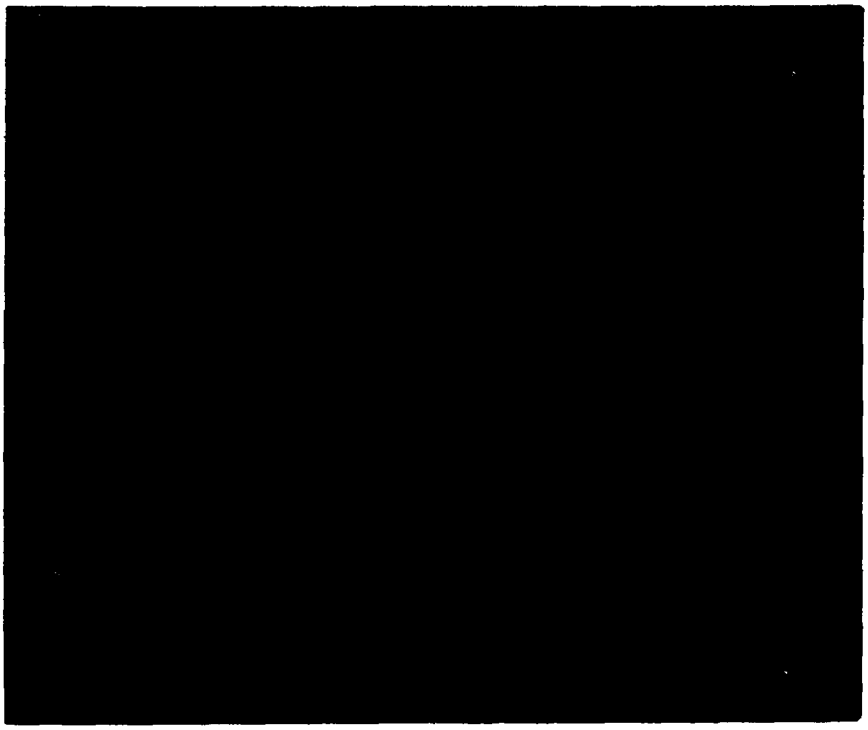
that watering to 25.8% moisture would just wet the soil to the bottom of the culture vessels if left overnight.

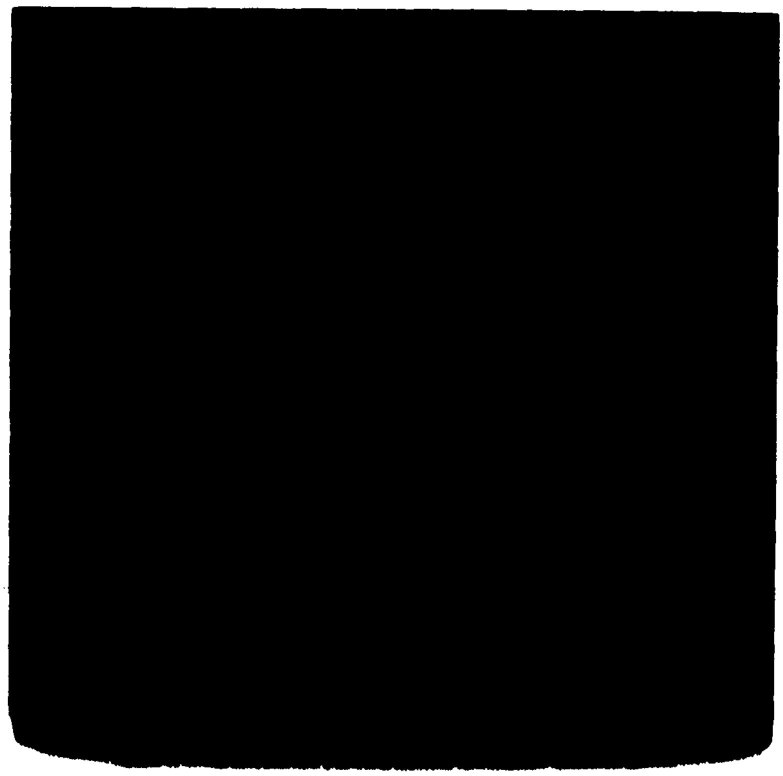
Thinning to three plants per pot was carried out upon unfolding of the unifoliate leaves. The trial was terminated some time after the development of distinct growth differences and leaf symptoms on July 13 and 14 in the four- to five-leafed stage. The plants were watered and placed inside for about two hours, then dissected and fresh weights recorded. The roots were washed out carefully, and the nodules removed, counted and weighed. The roots were evenly distributed throughout the entire volume of soil. There was no tendency for the roots to concentrate near the surface or at the drainage pipe under the chosen moisture conditions as may be seen from Plates 2, 3, and 4. This situation greatly enhanced the chances of uniform exploitation of the soil and fertilizers provided. The leaves, petioles with petiolules, stems, roots and remaining parts consisting of buds and pulvini were dried, weighed and ground in a Wiley mill for subsequent chemical analysis. The content of N, P, K, Ca and Mg was determined in the leaves and roots, and the first three elements only on the other parts. The contents were expressed as percent of dry weight and fresh weight and as the total per culture (product of dry weight and percent content x 100).

The 1963 experiment was planted on May 28. The total of 414 pots were placed in 6 rows about 120 feet long which were separated by planted border rows. The distance between rows was 40 inches. Preparation, watering and drainage of the pots was handled similarly to the previous year. The number of plants was reduced to ten per pot at

Plate 2. Uniform root distribution in top three inches of soil in pot experiment 1962

Plate 3. Uniform radial root distribution in pot experiment 1962





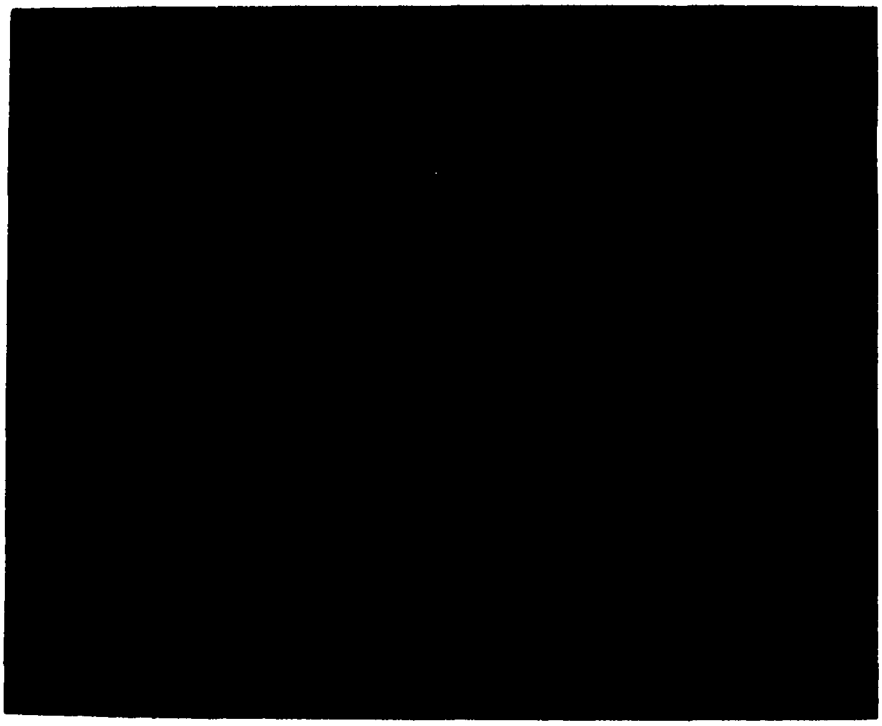


Plate 4. Root distribution in pot experiment 1962; absence of root accumulation at the bottom of the pot

emergence and to six plants per pot after unfolding of the second trifoliate leaves. This second thinning was used as the first sampling and the plants were separated into leaves and stems. Leaf symptoms were described daily as they appeared. One third of the pots was harvested at the six- to seven-leafed stage and fresh and dry weights of all parts recorded as in the previous year. All parts were ground for chemical analysis as in 1962. The nodules were collected, counted, weighed and kept in cold storage for subsequent analysis. One replication was subsequently sprayed with a mixture of "Nu-Iron" and "Nu-Zinc", made by the Tennessee Corporation, Atlanta, Georgia, at the rate of 6 lbs. per 100 gallons of water. "Nu-Iron" contains 30% iron, one half of which is present in chelated form. "Nu-Zinc" contains 55% zinc as oxysulfate. Another third of the pots was harvested at the end of flowering and similarly dissected in the laboratory. A portion of the leaves was cleaned and rinsed with deionized water while still fresh for minor element analysis. Fresh and dry weights were now also recorded for the pods. The remaining pots were grown to maturity for a yield test, seed size determination and chemical analysis of the seed. The percentages of P, K, oil and protein were determined on the soybean seed.

2. Field experiments

The field trial located on the Howard County Experimental Farm in 1961 was laid out on Cresco loam. The site had been under alfalfa since 1959. The main-plot size was 21 x 40 feet which accommodated four experimental rows (the subplots) and two border rows of 40 feet length.

The amount of fertilizer applied per acre covered the range from 0 to 400 lbs. of P by 50-lb. increments, 0 to 800 lbs. of K by 100-lb. increments and 0 to 2000 lbs. of Ca per acre by 250-lb. increments. P was applied as concentrated superphosphate (20% P), K as muriate of potash (50% K) and Ca as barn lime. The P and K and one-fourth of the Ca were applied about two weeks before planting and plowed under. The remainder of the Ca was then spread and disked in separately to reduce the possibility of P fixation.

The crop was planted on May 25. The varieties Ch, Bl, Hr and Hk mature in this order and were allotted to the subplots in this or the reversed order at random. The two outside varieties were bordered by their own kind. The field was wheel-hoed twice, hand weeded and cultivated several times. A row length of 2 feet was sampled at the end of flowering and the leaflets separated for chemical analysis. The content of N, P, K, Ca and Mg was determined on the leaflets after drying and grinding. The date of maturity and degree of lodging were recorded. Sixteen feet of each experimental row were harvested to measure yield of grain.

The initial soil fertility level of the area was evaluated from soil samples taken from six areas in the experimental field and at two depths (0-6 inches and 6-12 inches) before fertilization. Each sample was a composite of 3 borings about 10 feet apart. The soil analyses were carried out at the Soil Testing Laboratory of Iowa State University. The soil testing methods have been described by Hanway and Heidel (1952). P tested very low over most of the field. (1.0 to 2.5 pp2m P in the surface soil). A portion of the area had a P test of 3.5 pp2m which is sometimes considered as the limit for yield response in soybeans. K was low all over the trial field, although twice as high in the surface soil of replication I as in replication II where it reached 50 pp2m. Nitrifiable N tested low in the surface soil. It varied from 63 to 96 pp2m and fell to 24 to 57 pp2m in the subsurface layer. The soil reaction was acid with most pH values between 5.4 and 5.7 and a maximum range from 5.3 to 6.6.

Two years later, after harvesting the Chippewa crop in 1963, composite soil samples were taken from each main-plot at a depth of 0-12 inches. The soil test methods used were somewhat different from those used in 1961. Field moist soil was used for all tests. Mineralizable N was determined by a method described by Waring and Bremner (1964): Five grams of soil and 10 ml of water are incubated under anaerobic conditions for 1 week. The NH_4^+ content of an unincubated and an incubated sample are determined by steam distillation. The soil pH was read with a glass electrode in a 1 to 2 soil-water suspension. P was extracted with the Bray and Kurtz No. 1 phosphorus extractant (0.03 $\underline{N}$ NH_4F in 0.025 $\underline{N}$ HCl) in a 1 to 10 dilution ratio and determined colorimetrically using an ammonium molybdate solution and a reducing agent made up of 1-amino-2-naphtol-4-sulfonic acid, sodiumsulfite and sodium pyro-sulfite. K was extracted in a 1 to 5 dilution ratio with $\underline{N}$ ammonium acetate and determined by means of a flame photometer. The results clearly reflect the fertilization of 1961 even after a crop of corn in 1962 and a crop of soybeans in 1963 (Table 3).

Table 3. Soil test values from soil samples taken at the Howard County Experimental Farm two years after fertilization expressed as pH and pp2m N, P and K

Treatment number	Replication I				Replication II			
	pH	N	P	K	pH	N	P	K
1	6.00	59	50	141	6.28	35	43	94
2	6.09	26	76	114	6.28	35	81	97
3	5.72	35	36	216	6.03	37	33	140
4	6.16	30	56	162	6.25	18	57	101
5	5.91	46	38	132	6.08	32	32	103
6	6.27	28	79	118	6.42	32	48	96
7	6.23	31	42	162	6.25	34	29	134
8	5.95	39	48	125	6.28	36	56	133
9	5.94	39	22	93	6.43	27	35	78
10	5.87	36	45	84	6.06	25	83	78
11	6.26	30	46	214	5.95	20	26	108
12	5.90	28	59	235	6.12	28	59	176
13	5.97	37	31	86	6.57	19	37	86
14	6.19	37	66	104	6.66	24	100	98
15	6.23	35	22	147	6.32	20	36	156
16	6.07	41	70	214	6.27	26	65	111
17	5.85	33	15	74	5.95	34	16	52
18	5.74	29	94	63	5.78	29	61	64
19	5.51	28	13	229	6.06	33	20	189
20	5.35	39	100	291	5.79	29	73	181
21	6.21	25	20	71	6.46	25	14	65
22	6.20	44	98	57	6.70	28	94	49
23	6.60	28	15	250	6.72	15	15	199
24	6.65	29	92	250	6.60	38	80	213
25	5.95	38	39	108	6.00	38	50	145
26	5.98	33	20	157	6.40	36	21	116
27	5.93	27	99	153	6.10	18	67	108
28	5.93	26	50	60	6.20	34	35	63
29	5.62	20	56	266	6.39	39	32	261
30	5.71	23	46	106	6.15	35	61	88
31	6.42	27	64	146	6.30	45	24	93

[a]See Table 2 for treatment combinations applied in 1961.

The field trial located at the Carrington-Clyde Experimental Farm in 1961 was laid out on an area of Floyd silt loam. The rates of fertilization were the same as in the Howard County experiment with the difference that no calcium was applied and that the fertilizer was disked in rather than plowed under. The experiment was planted on May 26. The layout of the experiment, management, sampling and harvesting largely followed the same procedures as in the Howard County trial of 1961. All four varieties were sampled twice at short interval at about the end of flowering. The first sample was taken at the time when the varieties Ch and Bl had reached this stage. The second sampling, 9 days later, was chosen as an approximation for the other two varieties to reach this stage of development.

The initial fertility of the area was low. P tested low (4-6 pp2m) in the surface and very low (1-2 pp2m) in the subsoil. K also was low in the surface (100-136 pp2m) and somewhat lower in the subsoil. The pH was between 6.1 and 6.8 in the surface 6 inches of soil and between 6.0 and 6.5 in the 6-12 inch layer.

Chemical analysis of the ground plant material for P and K followed the analytical procedures described by Hanway (1962); dried and ground plant samples of 0.5 gm. are digested in concentrated H_2SO_4 using Cu as a catalyst. P is determined colorimetrically using vanadomolybdate. K is determined with a flame photometer using Li as an internal standard. N was determined on an aliquot from the same digest by steam distillation of NH_3 from an aliquot made alkaline with NaOH. The NH_3 was trapped in boric acid and titrated with 0.01984N H_2SO_4.[1] Ca and Mg were also determined on the same sulfuric acid digest by a modification of the method described by Ward and Johnston (1960). Fifty ml. of digest was heated until dry on a hot plate. Upon cooling the residue was resumed in 5 ml. of 6NHCl and diluted to 100 ml. Ca and Mg were determined on 10 or 20 ml. aliquots diluted to 200 ml. with deionized water to avoid phosphate interference during titration. The titration with disodium dihydrogen ethylenediaminetetraacetate dihydrate (EDTA) followed the procedure of Ward and Johnston whereby the Mg content is found as the difference of the amounts of EDTA used for (Ca plus Mg) and for Ca determination. Eriochrome Black T (Hack Chemical Company, Ames, Iowa) was used for the endpoint of the (Ca plus Mg) determination. Barnard *et al.* (1956) suggested triethanolamine as a solvent to reduce oxidation and polymerization of the indicator. Accordingly, 0.125 gms. of Eriochrome Black T were dissolved in 37.5 ml. triethanolamine and diluted to 50 ml. with distilled water.

A different indicator to that suggested by Ward and Johnston was used for the calcium endpoint. A calcein-thymolphtalein solution was prepared as a modification of a procedure described by Tucker (1957): 1 gm. of calcein W (G. Frederick Smith Chemical Co.) and 0.25 gm. of thymolphtalein are dissolved in 12 ml. of N NaOH and diluted to 50 ml. with distilled water.

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[1]The N, P, K analyses were carried out in the Soil Fertility Laboratory under the direction of Dr. J. J. Hanway.

Oil and protein content were determined on ground soybean material at the U. S. Regional Soybean Laboratory at Urbana, Illinois.

D. Statistical Methods

The statistical analysis followed the principles given by Anderson and Bancroft (1952). Other procedures used have been described in detail by Snedecor (1956) and Williams (1959). The quadratic form of the multiple regression equation was employed to relate the yield of soybeans, the dry weight production of various plant parts, and any relevant growth characteristics for which quantitative measurements were recorded each in turn as dependent variables to the fertilizer input factors.

The equation fitted to the data in most cases was of the form

$$Y = b_o + b_1P + b_2K + b_3Ca + b_{11}P^2 + b_{22}K^2 + b_{33}Ca^2 + b_{12}PK + b_{13}PCa + b_{23}KCa + b_{123}PKCa,$$

where the elements refer to those applied as fertilizer or limestone.

Ca was not involved as a variable in the field experiment at the Carrington-Clyde Experimental Farm and the model was reduced accordingly.

The rates of application given in Tables 1 and 2, previously, served as the design matrix after correction of the calcium rates for the amount of calcium contained in the phosphate application. The assumption was thereby made that the two sources of calcium were equally available to the plant.

The yield of soybeans as a dependent variable can be similarly expressed as a function of the chemical composition of a certain plant part or a combination of terms from several plant parts if this is biologically meaningful. In this study the yield of soybeans, the weight of roots and plant tops and the weight of leaves produced by the plant served as dependent variable in this type of relationship. The independent variables were entered as deviations from their overall means to avoid computational difficulties in obtaining an inverse matrix. The model fitted in the case that the percentage content of five nutrients in the plant tissue was known was of the form

$$
\begin{aligned}
Y = b_o &+ b_1\underline{P} + b_2\underline{K} + b_3\underline{Ca} + b_4\underline{Mg} + b_5\underline{N} + b_{11}\underline{P}^2 + b_{22}\underline{K}^2 + b_{33}\underline{Ca}^2 \\
&+ b_{44}\underline{Mg}^2 + b_{55}\underline{N}^2 + b_{12}\underline{PK} + b_{13}\underline{PCa} + b_{14}\underline{PMg} + b_{15}\underline{PN} + b_{23}\underline{KCa} \\
&+ b_{24}\underline{KMg} + b_{25}\underline{KN} + b_{34}\underline{CaMg} + b_{34}\underline{CaN} + b_{45}\underline{MgN} \;.
\end{aligned}
$$

In this case the underscore denotes the concentration of this element in the plant part.

Miller (1960) sampled various plant parts at several stages of development to determine with which of these soybean yields correlated best. The relationships based on chemical composition at the end of flowering were as good or better than at other stages of development and it was found that upper leaves and petioles could be used equally well. He also compared the square root and quadratic forms of regression equations and found little reason for preference under the conditions. In the present work leaf composition at the end of flowering was used to express the relationships between yield and composition of the plant.

The computation of the X′X matrix, the X′Y-products, the elements of the inverse matrix, the partial regression coefficients, their standard deviations and the value of t to test the null hypothesis that the partial regression coefficients are equal to 0 was performed on an IBM-7074 computer at the Iowa State University Computation Center.

The general procedure was to obtain similar equations for each variety in the experiment. Sets of analogous partial regression coefficients can then be tested for differences among them by F-tests (Williams, 1959). The difference between a partial regression coefficient for a certain fertilizer effect in a regression equation and a corresponding coefficient from a similar equation for another variety amounts to a measure of differential response since it expresses the amount by which the effect of a fertilizer factor on one variety fails to be the same as for another variety. Therefore it appears justified to introduce "error b" from the analysis of variance as denominator in the F-test when dealing with split-plot designs rather than the combined deviations from regression as proposed by Williams. The general formula to calculate the mean square for the numerator in the F-test is:

$$MS = \frac{\sum_r \frac{b_{ri}^2}{t_r^{ii}} - \bar{b}_i^2 \sum_r \frac{1}{t_r^{ii}}}{m-1}$$

where t_r^{ii} is the c_{ii} element for the rth set,

$\bar{b}_i$ is the weighted mean of the coefficients b_{ri}:

$$\bar{b}_i = \frac{\sum_r \frac{b_{ri}}{t_r^{ii}}}{\sum_r \frac{1}{t_r^{ii}}}$$

and m is the number of sets of data. In the special case where the t_r^{ii} are the same in each set, and using 4 sets, the formula simplifies to

$$MS = \frac{\sum_r b_{ri}^2 - 4\bar{b}_i^2}{3c_{ii}},$$

where $\bar{b}_i$ is the mean of the coefficients b_{ri}.

Where only two varieties are involved, the difference in response between varieties was tested by t-test using the formula

$$\underline{t} = \frac{b_{1i} - b_{2i}}{c_{ii}\, s_e^2 \cdot 2},$$ where s_e^2 denotes the experimental error from the analysis of variance. This t-test is identical with Williams' F-test when two varieties are being compared as shown in the Appendix.

Combination of individual regression equations can be carried out unless heterogeneity of variance is indicated by Bartlett's test (Snedecor, 1956, p. 286). To develop a combined equation for the four varieties some arbitrary decisions have to be made with regard to the level of significance required for factors to enter the equation.

Coefficients reaching significance at the 0.20 level of probability or better in a t-test in one or more varieties are selected. If in addition there appear differences among the 4 varieties with respect to such a factor as judged by significance at the 0.25 probability level in a F-test on the deviations of the individual partial regression coefficients from their mean then that factor is replaced by 4 terms representing its interactions with dummy variables for the varieties. This allows a final test on the significance of varietal differences as expressed in the combined equation.

Duncan's multiple range procedure (Duncan, 1945) can be adapted to test the differential responses expressed by the difference between partial regression coefficients. A standard error can be computed using the quantity

$$s_{b_i - b_{i'}} = \sqrt{\frac{c_{ii} - 2c_{ii'} + c_{i'i'}}{2} s_{e_b}^2}$$

as standard error, where $s_{e_b}^2$ represents error b of the analysis of variance in case of a split-plot design. The c_{ii} and $c_{i'i'}$ are the inverse matrix elements for the interactions of an independent variable on a variety basis and the associated dummy variable. The required off-diagonal $c_{ii'}$ elements are known since the combined regression equation is used for this test on differential responses.

When the independent variables represent fertilizer treatment combinations or soil fertility values applying to whole plots the inverse elements are equal for comparison of any two varietal regression coefficients in a set of b_i and the computations are simplified. Duncan's multiple range test provides a check on the conclusions based on William's F-test and specifies the varieties which actually differ in a particular response.

In order to arrive at prediction equations further terms may be deleted upon inspection of the individual _t_-values in the combined regression using the same criterion as before. Linear terms are maintained when the factor also occurs in a qualifying interaction term. Partial regression coefficients were expressed on the basis of 100 lbs. of P, K and Ca per acre applied for all equations designated as prediction equation. Elsewhere, the coefficients are based on the coded treatment combinations of the statistical design used. Production surfaces and isoquants may be calculated using the partial regression coefficients of the fitted regression equations (Heady _et al._ 1955). A vertical projection of the isoquants was used to illustrate the magnitude of responses and differential responses over the range of fertilizer input. The nature of the isoquant curves may be of one of three types depending on the terms deleted from the full model and on the signs of the partial regression coefficients for quadratic terms. The graph of a quadratic equation is either elliptic, hyperbolic or parabolic in nature. It is elliptic when two squared terms are involved of the same sign, hyperbolic if they have unlike signs and parabolic if one squared term was deleted from the equation.

Ellipsoidal production surfaces are often preferred because they reflect the decrease in yield known to exist at excessive levels of nutrient input. They require that quadratic terms be retained irrespective of their significance. On the basis of previous knowledge or assumed behavior of the variable it may be desirable to restrict deletion of squared terms to the case where none of the terms containing that factor are of any consequence and all can be deleted. In cases involving the yield of soybeans, this reasoning was followed to retain the squared terms of P and K. Actually a downward trend may not follow at once after maximum production is reached and the question of whether a quadratic term should be maintained or deleted can be resolved satisfactorily only by testing a wider range of models. In most cases all three forms of production surface are acceptable provided no attempt is made to extrapolate outside the area investigated, a procedure for which quadratic polynomials are notoriously untrustworthy anyway.

III. FIELD EXPERIMENTS WITH VARIETIES GROWN IN IOWA

A. Field Experiment at the Howard County Experimental Farm; Results and Discussion

1. Yield of soybeans as a function of fertilizer input and soil fertility variables

The analysis of variance for yield of soybeans in Table 4 shows a highly significant effect of fertilizer treatments and highly significant differences between varieties. The fertilizer x variety interaction reached significance at the 0.05 probability level.[1]

The multiple regression of the yield of soybeans on the fertilizer input variables was run for each variety and the partial regression coefficients tested using deviations from regression. The analysis of variance of the regression presented in Table 5 shows that the yield of all varieties was strongly affected by fertilization.

The regressions in Table 6 present cases of a very strong effect of K on the yield of soybeans for all 4 varieties. The linear response to K is of the order of 4 bushels per 100 lbs. of K per acre.

The residual effect of fertilization after two years can be assessed from the 1963 results for the variety Ch. Ignoring the possible effects of seasonal differences the two sets of coefficients are clearly related (Table 6). The effect of K applied in 1961 on the yield of

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[1]The symbols used to indicate the significance levels 0.01, 0.05, 0.10 and 0.25 (or 0.20 for *t*-tests) in this dissertation are, respectively, **, *, ++ and +.

Table 4. Analysis of variance for the yield of soybeans in the field experiment at the Howard County Experimental Farm

Source	Degrees of freedom	Mean squares	F
Main plots	61		
Replications	1	0.0031	
Fertilizers (F)	30	194.9237	4.89**
Error a	30	39.8982	
Sub-plots	186		
Varieties (V)	3	526.5653	56.04**
F x V	90	14.2880	1.52*
Error b	93	9.3974	

Table 5. Analysis of variance of the multiple regressions for the yield of soybeans of four varieties grown at the Howard County Experimental Farm

Source	Degrees of freedom	Mean squares			
		Ch	Bl	Hr	Hk
Total	61	--	--	--	--
Regression	10	167.8211**	106.2116**	126.6252**	81.8544**
Deviations	51	20.6080	15.2320	33.2977	23.8732

Table 6. Partial regression coefficients relating the yield of soybeans of four varieties to fertilization and their significance

	Year and variety				
	1961				1963
Factor	Ch	Bl	Hr	Hk	Ch
b_o	26.8735**	27.6679**	32.2739**	28.0515**	27.6787**
P	0.5984	-0.0641	-1.4656	-0.1641	0.2722
K	4.6481**	4.2422**	3.8066**	4.0443**	1.5685**
Ca	0.1688	0.4443	1.0302	-0.6774	1.1003+
P^2	-0.1628+	-0.0001	0.1409	-0.0080	-0.0439
K^2	-0.5304**	-0.4991**	-0.4295**	-0.4205**	-0.1352++
Ca^2	-0.0030	-0.0245	-0.1296	0.0659	-0.1133+
PK	0.1634+	0.0847	0.1530	0.0351	0.0183
KCa	-0.0897	-0.0248	0.0770	0.0039	-0.0152
PCa	-0.0146	-0.0808	0.0386	0.0485	-0.0370
PKCa	0.0107	0.0114	-0.0070	0.0036	0.0095
R^2	0.6149	0.5776	0.4271	0.4020	0.5175

soybeans grown two years later was significant at the 0.05 level of probability. The linear effects of P and K were reduced by a factor of 0.5 and 0.33 respectively, whereas that of Ca was 6.5 times stronger and reached the 0.20 level of significance. This emphasizes the recognized fact that responses to liming may not develop fully in the year of application and may be at least a partial explanation for the lack of response to Ca in the first year. In agreement with the above the residual PK interaction effect is smaller and the PCa interaction effect is stronger than in the year of fertilization.

Williams' procedure when applied to sets of four corresponding partial regression coefficients led to the results given in Table 7. It appears from the data in Table 7 that there were no significant

Table 7. F-tests on differential yield responses of four varieties to fertilization

Factor	Mean squares	F
b_o	13.9120	1.48
P	11.4951	1.22
K	2.1511	< 1
Ca	8.5996	< 1
P^2	22.0907	2.35++
K^2	4.0693	< 1
Ca^2	9.3230	< 1
PK	6.6899	< 1
KCa	10.3848	1.11
PCa	6.7092	< 1
PKCa	4.8880	< 1

differences between the varieties due to varietal characteristics when unfertilized or in their yield response to fertilizers at the 0.05 level. There was a difference in the quadratic effect of P at the 0.10 level. This can be related to the non-conformity of Hr in this respect. It had a positive regression coefficient for P^2 whereas the others were negative. It is likely that this is the interaction which was indicated by the significant F x V interaction in the analysis of variance.

Soil test values obtained for each plot two years after the experiment were employed in an attempt to remove an additional portion of the plot to plot variation not explained by regression. The result of fitting an equation including four soil test variables and their squares, and providing for a number of interaction effects with the applied fertilizers is shown in Table 8.

Table 8. Partial regression coefficients relating the yield of soybeans to fertilizer application in 1961 and soil fertility factors measured in 1963, their significance and differential yield responses of four varieties

Factor[a]	Variety: Ch	Bl	Hr	Hk	Mean square	F
b_o	28.4371+	34.8014*	59.4186*	69.2701**	1.7496	< 1
P_f	12.4046*	6.8806+	-4.1697	-1.6744	31.9164	1.459+
K_f	-4.8215	-3.3629	-3.8309	-8.2448+	5.6196	< 1
Ca_f	-4.0005*	-2.8146++	-0.0646	-3.8511+	17.4770	< 1
P_f^2	-1.0783++	-0.5926	0.6195	0.2012	34.6946	1.586+
K_f^2	-0.2342	0.1031	0.1664	0.5528	5.8872	< 1
Ca_f^2	0.4526*	0.4175*	-0.0884	0.3225	21.4140	< 1
P_fK_f	0.0398	0.1371	-0.0355	0.0482	2.0080	< 1
K_fCa_f	0.0712	0.0605	0.0329	0.2748	4.0241	< 1
P_fCa_f	-0.1678	-0.2552	-0.1664	0.0099	3.4467	< 1
$P_fK_fCa_f$	0.0196	0.0067	0.0790	-0.0042	6.8617	< 1
pH	29.1019++	7.7376	-7.5910	14.5877	12.7889	< 1
N_s	-0.1471+	0.1058	-0.0824	0.0200	19.1611	< 1
P_s	-0.8372+	-0.3554	0.4286	0.3334	22.0274	1.007
K_s	0.4011**	0.2957*	0.3366++	0.4827*	5.5628	< 1

[a]The subscript f indicates that fertilizer was the source of supply for this nutrient. The subscript s indicates that soil was the source of supply.

Table 8. (Continued)

Factor	Variety Ch	B1	Hr	Hk	Mean square	F
$(pH)^2$	-20.1043	9.3735	-38.3827	-9.3339	6.8080	< 1
N_s^2	0.0121++	-0.0023	0.0093	0.0017	18.8647	< 1
P_s^2	-0.0003	0.0011	0.0093+	0.0033	11.2334	< 1
K_s^2	-0.0001	0.0000	0.0003	0.0003	7.9030	< 1
pHP_f	-9.9943++	-6.7227	-3.8309	-5.1301	3.2961	< 1
pHK_f	1.4797	-0.4189	3.4030	-4.1361	17.0213	< 1
$pHCa_f$	4.0680	7.7354+	9.8668	6.2698	2.9667	< 1
$pHP_f^{\ 2}$	0.8703+	1.0194++	0.4377	0.9271	3.1247	< 1
$pHCa_f^{\ 2}$	-0.8004+	-1.2692*	-0.7469	-0.8024	2.8968	< 1
pHP_fK_f	-0.0460	0.0496	-0.7849	0.0325	9.8027	< 1
pHP_s	0.4431+	-0.0612	0.3632	-0.1995	14.3358	< 1
pHK_s	-0.1779+	-0.0289	-0.1442	0.0535	11.6340	< 1
N_sP_s	0.0028	-0.0060+	0.0082	0.0045	22.0282	1.007
P_sP_f	0.1304	0.0469	-0.2034	-0.1241	21.6268	< 1
$P_sP_f^{\ 2}$	-0.0012	0.0014	0.0095	0.0074	9.3824	< 1
P_sK_s	0.0002	-0.0004	-0.0007	-0.0005	3.8109	< 1
K_sK_f	-0.1290**	-0.0791*	-0.1174*	-0.1367*	6.7441	< 1
$K_sK_f^{\ 2}$	0.0107**	0.0057++	0.0094*	0.0094*	7.2414	< 1
R^2	0.830	0.803	0.705	0.589		

The multiple R^2 was raised from an average of 0.505 to 0.732. The multiple regression on the soil fertility factors after fitting the fertilizer input factors, however, was not significant when tested by F-tests for each variety. This indicates that the additional variation removed was not significant (Table 9). It is relevant to point out in this connection that inclusion of a large number of factors in regression may have the effect of decreasing the residual mean square to an extent leading to underestimation of error variance.

Homogeneity of variance is required for obtaining valid F-tests on differential effects. This condition is not always satisfied in the regression equations being considered and is partly due to the nature of Bartlett's formula:

$$\chi^2 = 2.3026\ (n-1)\ (a \log \bar{s}^2 - \Sigma \log s^2),$$

where (n-1) is the number of degrees of freedom associated with the individual error terms, and a is the number of sets of data being combined. Assuming several multiple regressions on the same sets of data, the value of χ^2 seems to vary with the number of degrees of freedom of the residual mean squares. If a large number of terms is fitted in one set of equations and this number is subsequently reduced in another set by elimination of certain meaningless factors, then it may occur that the residual mean squares are hereby not altered appreciably. The value of χ^2 would then vary inversely with the number of variables fitted.

Apparently, in the case of yield of soybeans the χ^2 value may or may not reach significance depending on the type of analysis used (Table 10). It seems that Bartlett's formula is not completely satis-

Table 9. Analysis of additional variance removed from the residual sum of squares by inclusion of soil fertility values in multiple regressions for the yield of four varieties

Source	Degrees of freedom	Variety	Sum of squares	Mean squares	F
Regression on fertilizer input factors	10	Ch	1678.211		
		Bl	1062.116		
		Hr	1266.253		
		Hk	818.544		
Regression on fertilizer input and soil test values	32	Ch	2265.966		
		Bl	1476.392		
		Hr	2091.185		
		Hk	1198.390		
Difference	22	Ch	587.755	26.716	1.672
		Bl	414.276	18.831	1.506
		Hr	825.932	37.542	1.247
		Hk	379.846	17.266	< 1
Residual	29	Ch	463.248	15.974	
		Bl	362.657	12.505	
		Hr	873.320	30.110	
		Hk	837.712	28.886	
Total	61	Ch	2729.214		
		Bl	1839.049		
		Hr	2965.505		
		Hk	2036.102		
Tabular F (0.05)					1.940

factory for testing homogeneity of variance among multiple regressions involving large numbers of degrees of freedom in the residual mean square. The calculated χ^2 values are sufficiently large, however, to restrict the interpretative value of F-tests on differential effects derived by the use of combined residual error terms.

Table 10. χ^2 values on residual mean squares for various types of analysis

Type of analysis	Residual degrees of freedom	Residual mean squares				
		Ch	Bl	Hr	Hk	χ^2
Analysis of variance	30	15.281	15.332	31.005	17.623	5.500 (n.s.)
Regression	51	20.608	15.232	33.298	23.873	8.0151*
Regression	29	15.974	12.505	30.110	28.886	7.861*
Tabular χ^2 (0.05) at 3 d.f.						7.815

Next considering the results of the multiple regressions including terms for soil fertility values it may be seen that a complete change in the location of significant effects occurred in comparison to equations involving fertilizer input factors only. While the latter indicated the high level of significance of the linear and quadratic effects of K on the yield of soybeans, the effect of applied K was insignificant where soil fertility values were included in the equation. Instead, P, Ca and Ca^2 effects appeared for the varieties Ch and Bl to various levels of significance. Among the soil fertility variables the K effect was consistently significant over all varieties and so were the interaction terms of $K_s \times K_f$ and $K_s \times K_f^2$. It seems that the significance of applied K has been transferred to the factor K_s in conjunction with the negative $K_s \times K_f$ interaction term. Since the soil fertility values are entered as deviations from their mean K_s may assume negative values. As the value of K_s enters the negative range the $K_s \times K_f$ interaction begins to contribute a positive effect to applied K. In other words, at relatively low fertility levels of K in the soil the effect of applied K will be larger.

It is noticeable that the number of terms reaching significance at various levels and also the value of the multiple R^2 values decrease in the order Ch, Bl, Hr, Hk which is the order of increasing maturity date. Other factors possibly exert a greater influence on the yield of the variety with the longer growing period.

Differential effects between varieties were calculated for all terms in the equation using the general formula given by Williams (1959). The last two columns of Table 8 show the results of Williams' test using the combined residual mean square as error term. The four varieties differed with regard to the linear and quadratic responses to P fertilizer to the 0.20 level of significance. This finding confirms that obtained with the shorter equation given in Table 6.

It should be remembered that the soil test values in this case include, besides an estimate of natural soil fertility levels, some measure of the residual effect of the fertilizers applied as well as a possibly considerable bias due to any events which took place during the two year period between trial and soil sampling. This special nature of the soil test values renders the equations unsuitable for predictive purposes.

It seems that the results of the regressions involving soil fertility variables can be explained logically. The technique could be used to advantage under favorable conditions and when soil test values are obtained prior to running the experiments. In the present study, however, soil fertility values will not be included in the regression equations for the reasons just discussed.

The yield equations for the four varieties may be combined as follows on the basis of conclusions reached in the earlier part of this discussion:

$$Y = b_{och}\, Ch + b_{oBl}\, Bl + b_{oHr}\, Hr + b_{oHk}\, Hk + b_1 P + b_2 K + b_{11Ch} P^2\, Ch$$
$$+ b_{11Bl} P^2\, Bl + b_{11Hr} P^2\, Hr + b_{11Hk} P^2\, Hk + b_{22} K^2 + b_{12} PK.$$

The partial regression coefficients for this equation are given in Table 11. Tests on the coefficients involving varieties were made using error b of the analysis of variance. Fertilizer effects were tested using error a. In addition to the K and K^2 effects which were recognized before, the PK interaction now shows a highly significant effect.

Differences involving varieties were compared by means of Duncan's multiple range test (Table 12). There was a varietal difference between Hr and the three other varieties at the 0.01 level of significance. A significant differential response to P existed between Hr and Ch.

Individual yield prediction equations for each of the varieties are shown in Table 13. The significance of the partial regression coefficients was tested using the experimental error from the analysis of variance.

Isoquant maps have been drawn for the varieties Ch and Hr using the above yield prediction equations. Differences between Figures 1 and 2 express the largest differential effects existing among the four

Table 11. Partial regression coefficients of the combined yield equation for four varieties and their significance

Factor	b_i	t
Ch	28.2001	33.82**
Bl	27.9833	33.56**
Hr	32.7752	39.30**
Hk	27.1826	34.12**
P	-0.2256	< 1
K	4.2172	6.34**
Ch x P^2	-0.0460	< 1
Bl x P^2	-0.0249	1.13
Hr x P^2	0.0148	< 1
Hk x P^2	-0.0004	< 1
K^2	-0.4785	6.20**
PK	0.1320	2.76**
R^2	0.5409	

Table 12. Comparison of corresponding partial regression coefficients in the combined yield equation for four varieties using Duncan's multiple range test

Nature of differential response	Variety, regression coefficients and significance of differences[a]			
Variety	Hk	Bl	Ch	Hr
	27.1826	27.9833	28.2001	32.7752
P^2	Ch	Bl	Hk	Hr
	-0.0460	-0.0249	-0.0004	0.0148

[a]Comparisons failing to reach the 0.05 level of significance are underlined with a solid line. In addition, those reaching the 0.05 level but not the 0.01 level of significance are underlined with a broken line.

Table 13. Partial regression coefficients, b_i, of yield prediction equations for individual varieties expressed in bushels per 100 lbs. of P and K applied per acre and their significance

Factor	Ch		Bl		Hr		Hk	
	b_i	$\underline{t}$	b_i	$\underline{t}$	b_i	$\underline{t}$	b_i	$\underline{t}$
b_o	27.4896	20.34**	28.7470	21.27**	32.5834	24.11**	27.3216	20.21**
P	1.0422	0.39	-0.6554	0.25	-1.7656	0.66	-0.4258	0.16
K	4.2909	3.22**	4.2108	3.16**	4.5142	3.39**	3.8525	2.90**
P^2	-0.6400	1.04	-0.0604	0.10	0.3624	0.59	0.1116	0.18
K^2	-0.5315	3.44**	-0.5087	3.30**	-0.4788	3.10**	-0.3949	2.56*
PK	0.4112	2.15*	0.2800	1.46+	0.2564	1.34+	0.1084	0.57
R^2	0.6058		0.5670		0.4072		0.3762	

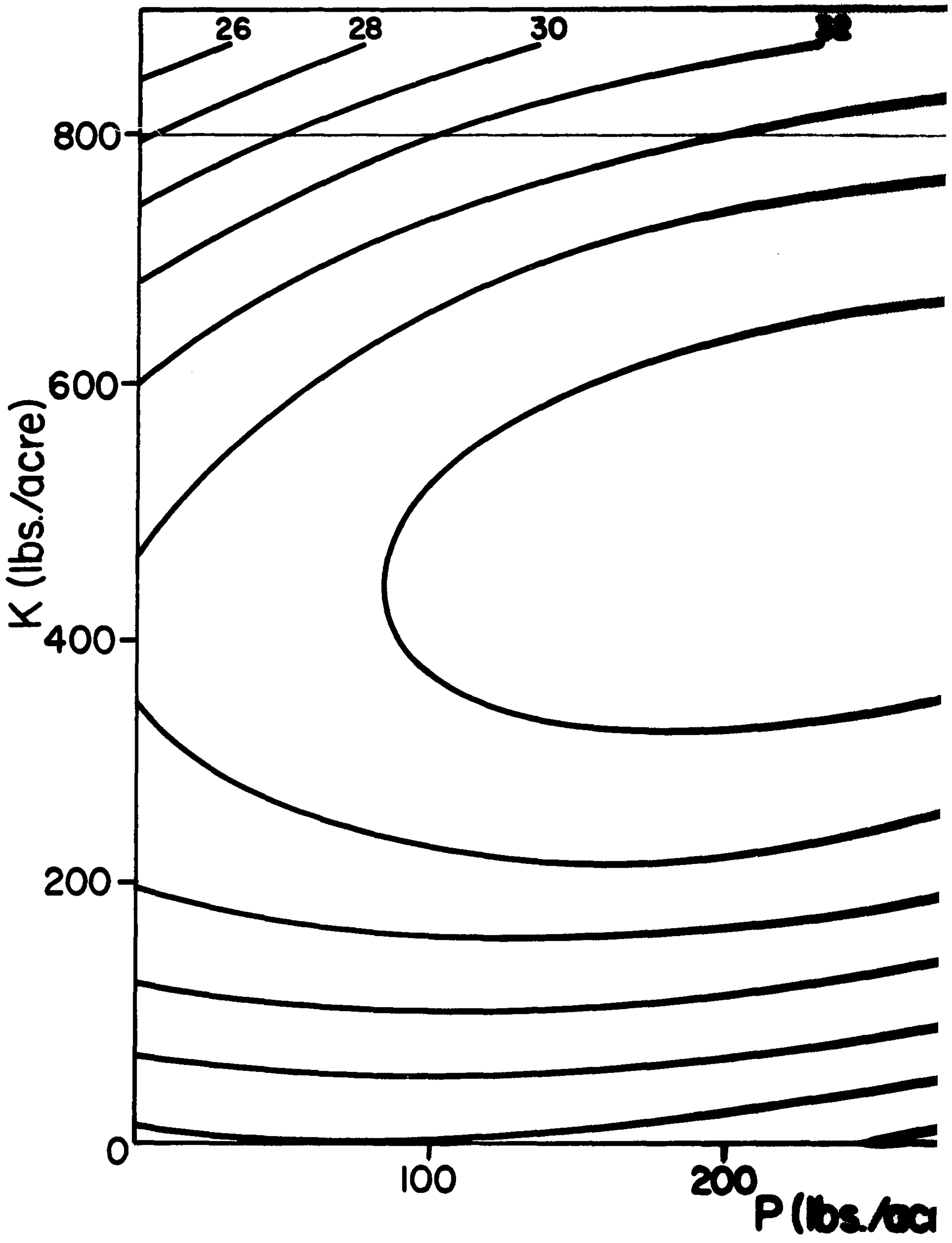
varieties in response to P application since the differential response between Ch and Hr was the only one to reach significance at the 0.05 level according to Duncan's multiple range test. At 500 lbs. of K per acre the response to 250 lbs. of P per acre is of the order of 2 to 3 bushels in the case of Ch and 1 to 2 bushels per acre in the case of Hr. It may be concluded that differential yield responses were significant but of small order.

Figure 1 shows that the yield of Ch will be reduced by as much as six bushels when the P application is raised from 0 to 400 lbs. at 0 K application. Benefit from P fertilization is obtained only at high rates of K application due to the significant effect of the PK interaction.

The combination of P and K fertilization for maximum yield of Ch was approximately 250 lbs. of P and 500 lbs. of K per acre; amounts which are unlikely to be applied in agricultural practice. The rate of K application leading to the maximum yield of soybeans at an arbitrary rate of 250 lbs. of P per acre can also be calculated by taking the partial derivative of the individual prediction equations with respect to K and equating to 0. In this case the rates of K for maximum yields of varieties Ch, Bl, Hr and Hk in this same order were: 500, 483, 538, and 522 lbs. per acre. At low rates of K application the yield responses are small. One hundred lbs. of K per acre (equivalent to 201 lbs. of muriate of potash) will raise the yield by approximately four bushels. Under existing crop rotation practices the effective quantity of K applied may be only a fraction of this amount and this could explain

Figure 1. Yield isoquants derived from the prediction equation for the variety Chippewa grown at the Howard County Experimental Farm, expressed in bushels of soybeans per acre and with applied P and K as variables

———————— Limits of area investigated



26
28
30
800
600
400
200
0
K (lbs./acre)
100
200
P (lbs./ac

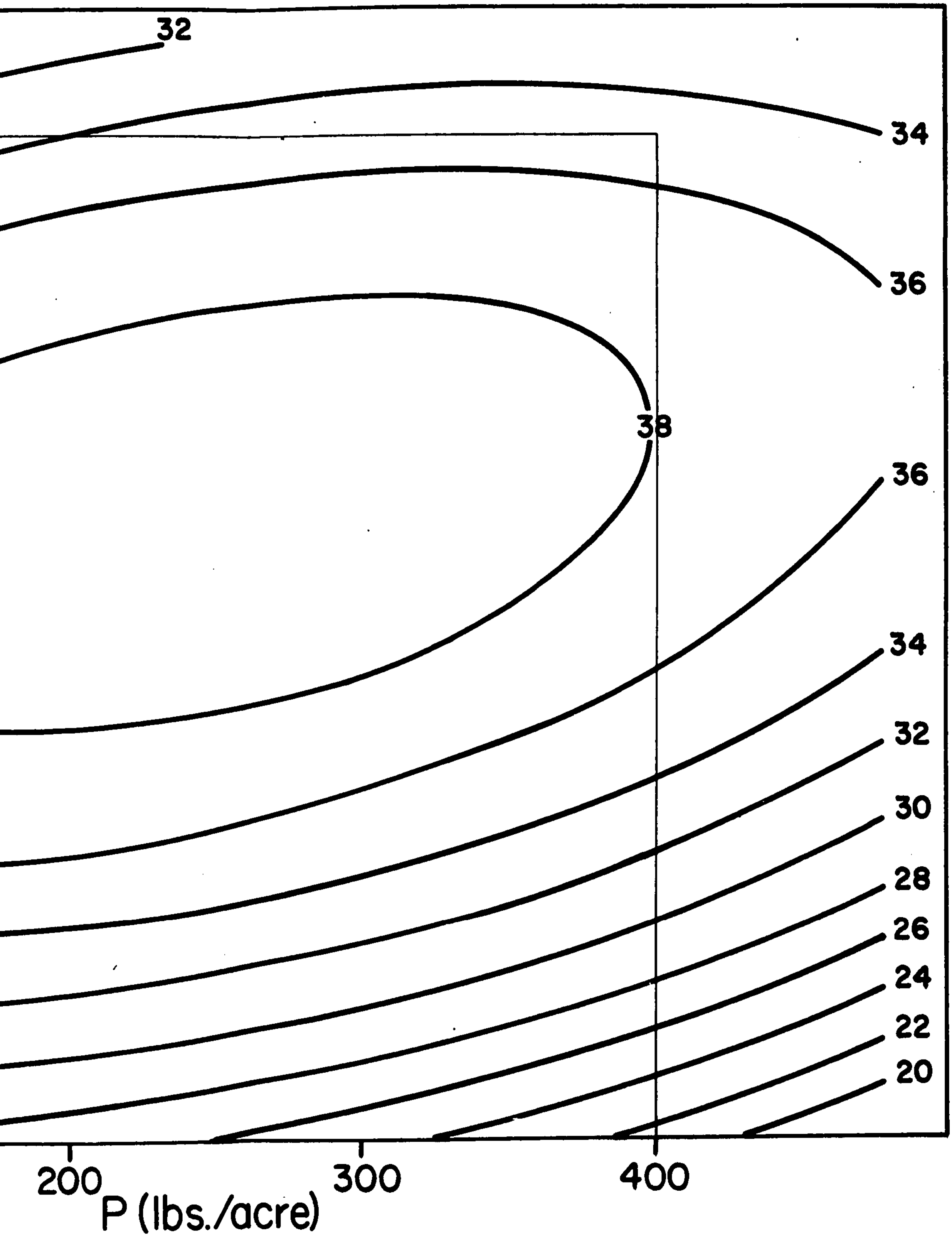
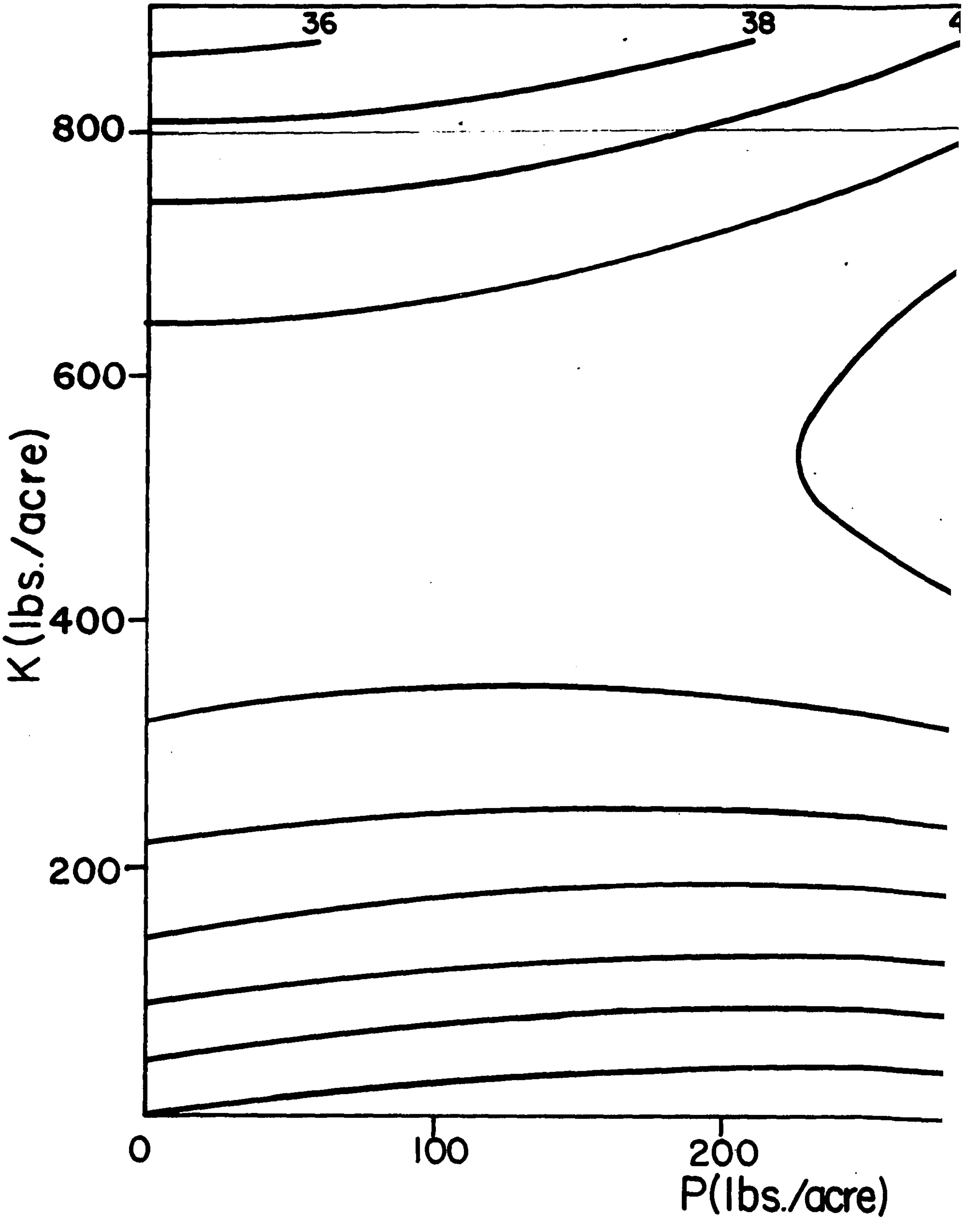
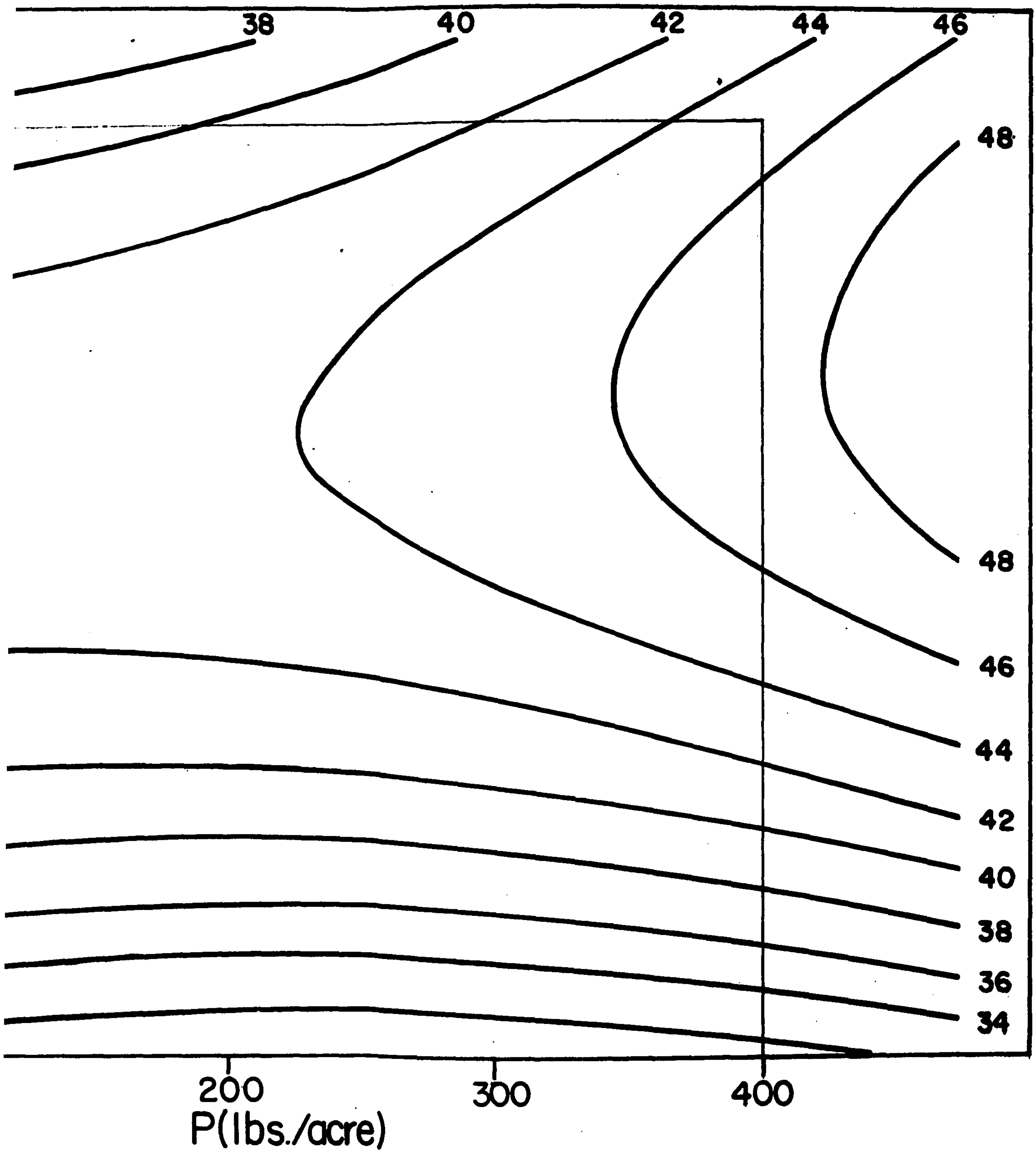

32
34
36
38
36
34
32
30
28
26
24
22
20
200
300
400
P (lbs./acre)

Figure 2. Yield isoquants derived from the prediction equation for the variety Harosoy grown at the Howard County Experimental Farm, expressed in bushels per acre and with applied P and K as variables

———————— Limits of area investigated


36
38
800
600
400
200
K(lbs./acre)
0
100
200
P(lbs./acre)


38
40
42
44
46
48
48
46
44
42
40
38
36
34
200
300
400
P(lbs./acre)

some cases where soybeans fail to respond to fertilization and yet yield better on land of high natural fertility.

2. <u>Leaf symptoms in relation to chemical composition of the leaves</u>

Leaf abnormalities in the field were pronounced within four weeks after emergence on plots receiving high P, or P and Ca application. The symptoms consisted of yellow interveinal discoloration and local necrosis at later stages. The end of flowering was delayed. When terminated in normal plants, flowering still occurred in the top two to five nodes of those affected. Ch was invariably worst affected, followed by Hr and Hk, while Bl often showed no symptoms (Plate 5). The width and height of the rows was reduced under high P treatments in all four varieties. The symptoms and order of varietal susceptibility agree with the findings of Howell and Bernard (1962). They may represent a case of P toxicity under field conditions, although the possibility of induced K or Zn deficiency may not be ruled out as will be discussed later in relation to the chemical composition of the leaves.

Symptoms may appear on plants which are to contain 0.44% P in the leaves, or higher, at the end of flowering. While this suggests that P toxicity causes the symptoms, it should be noted in Table 14 that in treatments 22 and 28 the percent K in the leaves is reduced somewhat below that of the healthy check plots (treatment 17) by Ca application. Therefore, there is the possibility of K deficiency as the causal factor. In treatment 18 the percent K is not affected by the high rate of P application. Although the percent K is equal to that in the check plots, a higher K content may be required where the P content in the leaf is

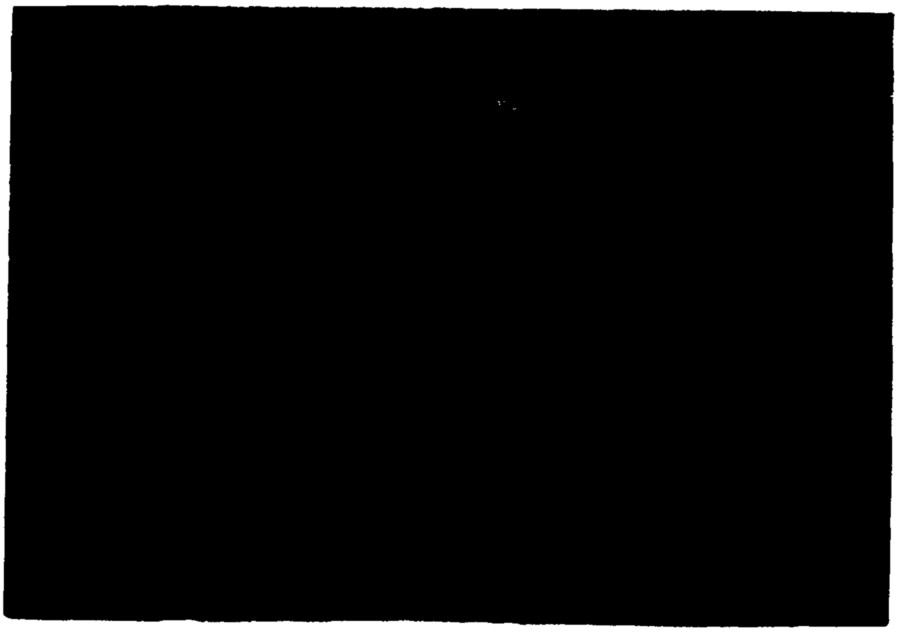


Plate 5. Leaf symptoms in the variety Chippewa at the Howard County Experimental Farm two years after application of high rates of P and Ca

Table 14. Leaf symptom development in relation to P and K content of the leaves of four varieties at the end of flowering

Treatment number	Coded rate of P	K	Ca	Var.[b]	Replication I %P	%K	Degree[a] of symptoms	Replication II %P	%K	Degree[a] of symptoms
17	0	0	0	Ch	0.28	0.90	0	0.36	0.90	0
				Bl	0.29	1.02	0	0.39	0.89	0
				Hr	0.29	0.99	0	0.35	0.84	0
				Hk	0.27	1.11	0	0.35	0.86	0
18	8	0	0	Ch	0.63	0.95	4	0.46	0.98	4
				Bl	0.44	1.11	2	0.39	0.89	0
				Hr	0.57	0.98	4	0.42	1.07	0
				Hk	0.46	1.11	3	0.42	0.89	0
20	8	8	0	Ch	0.41	2.01	0	0.39	1.92	0
				Bl	0.35	1.64	0	0.37	1.98	0
				Hr	0.39	2.68	0	0.38	1.55	0
				Hk	0.41	1.71	0	0.41	1.97	0
28	4	0	4	Ch	0.45	0.90	4	0.46	0.87	4
				Bl	0.41	0.91	0	0.38	0.92	0
				Hr	0.44	0.89	3	0.43	0.81	3
				Hk	0.44	0.68	1	0.44	0.81	0
22	8	0	8	Ch	0.49	0.86	4	0.48	0.80	4
				Bl	0.47	0.74	1	0.44	0.83	0
				Hr	0.49	0.89	3	0.55	0.84	3
				Hk	0.46	0.95	2	0.50	0.92	1
24	8	8	8	Ch	0.40	1.79	0	0.40	1.77	0
				Bl	0.40	2.00	0	0.39	1.83	0
				Hr	0.38	1.64	0	0.42	1.74	0
				Hk	0.41	1.73	0	0.40	1.62	0
10	6	2	2	Ch	0.39	1.47	0	0.42	1.38	0
				Bl	0.39	1.38	0	0.36	1.62	0
				Hr	0.41	1.17	0	0.45	1.59	0
				Hk	0.40	1.53	0	0.42	1.64	0
14	6	2	6	Ch	0.39	1.59	0	0.41	1.52	0
				Bl	0.39	1.25	0	0.38	1.67	0
				Hr	0.44	1.50	0	0.45	1.29	0
				Hk	0.40	1.59	0	0.43	1.74	0

[a]Relative degree of symptom development for experiment; 0 is none and 4 is severe.

[b]Variety.

doubled.

Raising the percent K by K application reduces the percent P to 0.44 or below in most cases, with the exception of Hr in treatments 10 and 14. Since plants not receiving K were smaller than others, this effect may be subscribed to correction of hidden K hunger whereby the percent P in the leaves was diluted due to increased plant size. This is not necessarily an indication that K deficiency caused the symptoms.

No conclusion can be made since the P content of the leaves does not fluctuate sufficiently in the field experiment. This difficulty has been overcome in several pot trials under different conditions. The results will be discussed in a later section of this dissertation.

3. Chemical composition of the leaves as a function of fertilizer input variables

a. Percent P in the leaves The analysis of variance in Table 15 shows highly significant fertilizer effects and differences between the varieties on percent P in the leaves. There are no differential responses to the nutrients applied as indicated by the virtual absence of the F x V interaction effect.

The multiple regressions listed in Table 16 for each variety show that the percent P in the leaves was affected by P and K application. The linear and quadratic components of the P and K effects and also the PK interaction effect reached significance at various levels of probability for most varieties.

Table 15. Analysis of variance for the percent P in the leaves sampled at the end of flowering at the Howard County Experimental Farm

Source	Degrees of freedom	Mean squares	F
Main plots	61	0.00007	< 1
Replications	1	0.01151	5.63**
Fertilizers (F)	30	0.00205	
Error a	30	0.00205	
Sub-plots	186		
Varieties (V)	3	0.00966	21.21**
F x V	90	0.00052	1.13
Error b	93	0.00046	

Table 16. Partial regression coefficients relating the percent P in the leaves at the end of flowering to fertilization and their significance

	Variety			
Factor	Ch	Bl	Hr	Hk
b_o	0.32815**	0.34238**	0.32431**	0.31659**
P	0.02989**	0.01970**	0.02743**	0.02534**
K	-0.01803*	-0.01488*	-0.01065+	-0.00675
Ca	0.01080+	0.00041	0.00613	0.00748
P^2	-0.00075	-0.00115++	-0.00114+	-0.00149*
K^2	0.00217**	0.00156*	0.00158*	0.00117++
Ca^2	-0.00112+	-0.00001	-0.00092	-0.00055
PK	-0.00219**	-0.00071	-0.00188**	-0.00069
KCa	-0.00009	-0.00015	0.00045	-0.00016
PCa	-0.00072	0.00016	0.00086+	0.00040
PKCa	0.00013	0.00005	-0.00008	-0.00007
R^2	0.7380	0.6459	0.7533	0.6706

The lack of differential responses among the varieties is borne out by the F-tests on the partial regression coefficients by Williams' technique, all of which, with one exception, are insignificant (Table 17). It therefore appears that the differential yield responses due to P application are not supported by differential responses in percent P. Possibly the total P content of the leaves may be differentially affected rather than the percentage. Several alternative explanations may be given: the chemical composition was evaluated for only one organ, the leaves, and at one particular time. The results may be different when other plant parts and stages of development are taken into account; the differential responses to P may be caused primarily by the effect of P on the uptake of other elements, or some other growth-controlling mechanism in the plant.

The percent P in the leaves of the four varieties can be combined into the following equation:

$$\text{Percent P} = b_o + b_1P + b_2K + b_3Ca + b_{11}P^2 + b_{22}K^2 + b_{33}Ca^2 + b_{12}PK + b_{13}PCa,$$

where the elements refer to those applied to the soil. The significance, in Table 18, of the partial regression coefficients, which were tested using the relevant error terms from the analysis of variance, agrees with the earlier analyses for the individual varieties.

Differential responses to the PKCa interaction were compared by means of Duncan's multiple range test. The variety B1 differed from all other varieties in its response to the PKCa interaction effect. The

Table 17. F-tests on differential responses in the percent P of the leaves among four varieties

Factor	Mean squares	F
b_o	0.00028	< 1
P	0.00029	< 1
K	0.00041	< 1
Ca	0.00032	< 1
P^2	0.00013	< 1
K^2	0.00024	< 1
Ca^2	0.00034	< 1
PK	0.00336	< 1
KCa	0.00018	< 1
PCa	0.00061	1.33
PKCa	0.00067	1.46+

Table 18. Partial regression coefficients of the combined equation for the percent P in the leaves of four varieties and their significance

Factor	b_i	*t*
b_o	0.32765	56.45**
P	0.02562	4.52**
K	-0.01253	2.45*
Ca	0.00626	1.22
P^2	-0.00113	1.90++
K^2	0.00162	2.70*
Ca^2	-0.00065	1.08
PK	-0.00138	2.96**
PCa	0.00017	0.37
Ch x PKCa	0.00001	0.22
Bl x PKCa	-0.00006	1.81++
Hr x PKCa	0.00004	1.20
Hk x PKCa	0.00005	1.49+
R^2	0.6359	

difference reached the 0.01 level of probability when Bl is compared to Hr and Hk.

Equations for prediction of the percent P for each variety individually are given in Table 19.

The contour map of the percent P in the leaves of Ch as a function of P and K applied at Ca = 0 is reproduced in Figure 3. In the absence of considerable differential response similar graphs for the other varieties would take a similar shape. The contours show that the percent P will rise with increasing rate of P application up to the limit of the investigated range. At low levels of K this effect is very strong and leads to the leaf symptoms described earlier. At high levels of K the rise in percent P flattens out at levels of P over 200 lbs. per acre. As was seen in Figure 1 this is the area of maximum yield of soybeans.

b. Percent K in the leaves The analysis of variance shows highly significant fertilizer treatment and variety effects on the percent K in the leaves and a virtual absence of differential responses between varieties (Table 20).

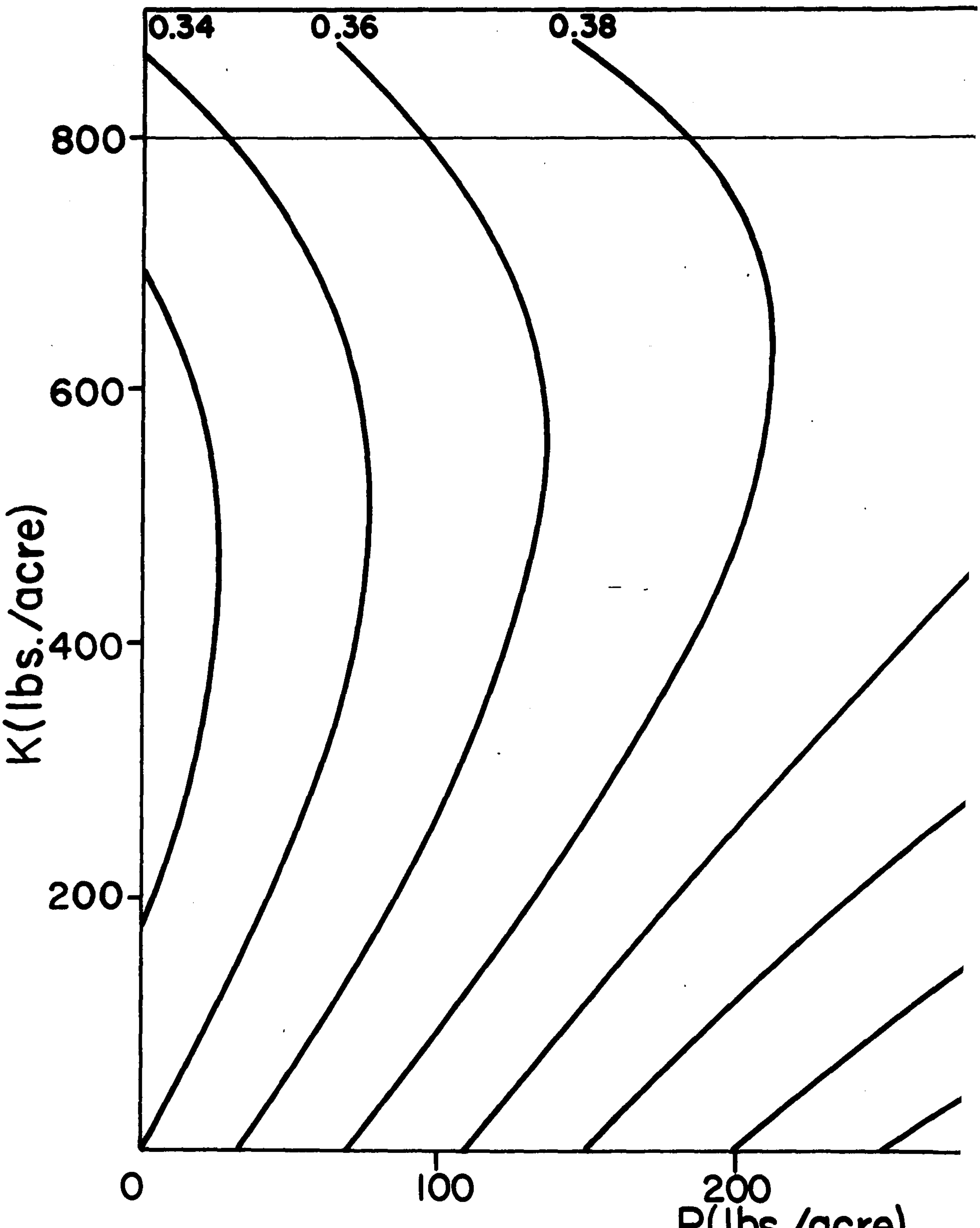
Multiple regression equations for the percent K in the leaves were derived for each of the four varieties and the partial regression coefficients are shown in Table 21. The K content of the leaves was strongly affected by the variety effect and by K fertilization. In the variety Bl the PCa interaction was a significant factor. The quadratic component of the P effect had a less significant effect in some cases. Comparison of corresponding partial regression coefficients between varieties showed that the four varieties differed in their response to K (Table 22);

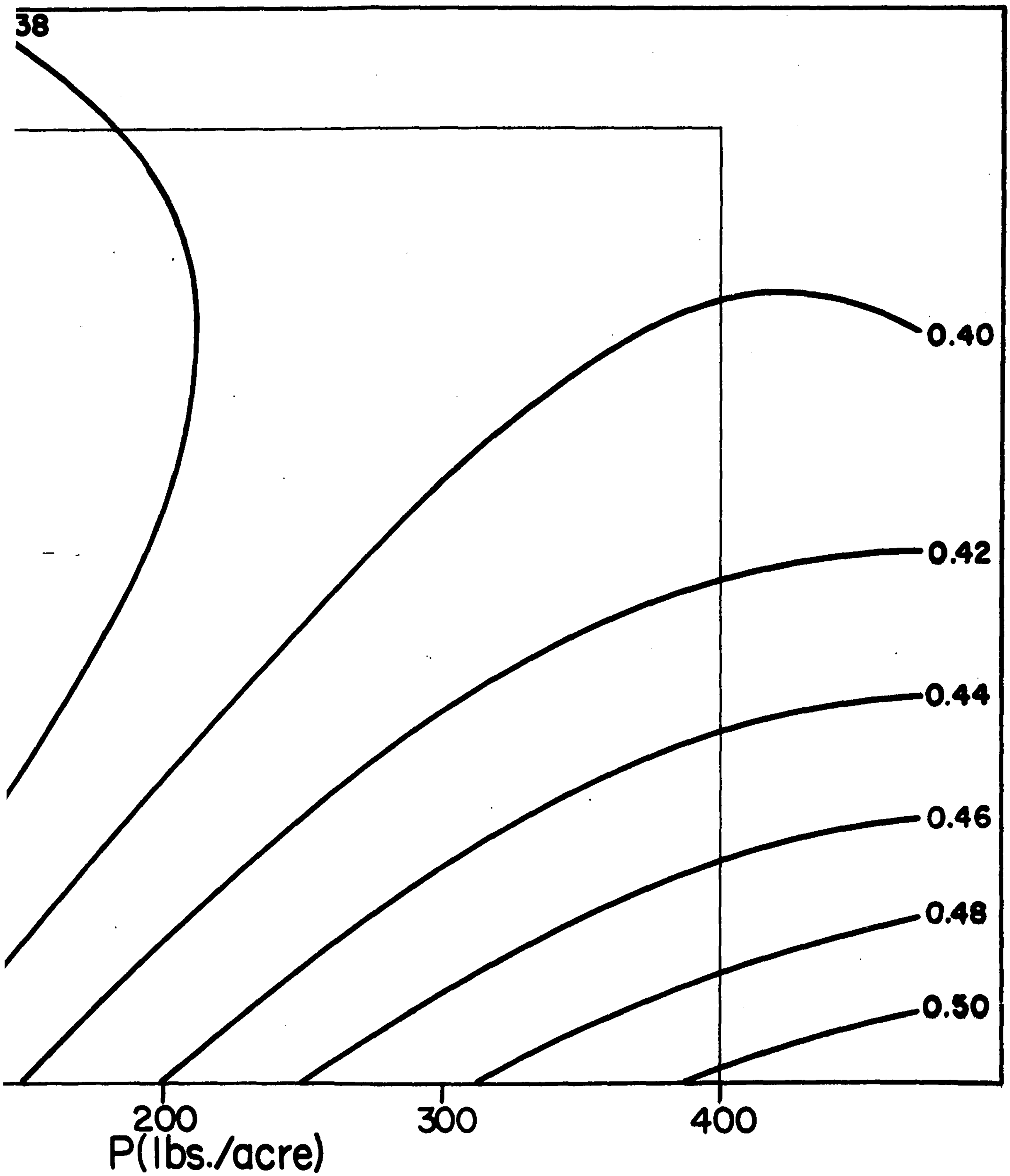
Table 19. Partial regression coefficients, b_i, of the equations for prediction of the percent P in the leaves at the end of flowering for individual varieties, expressed as percent P per 100 lbs. of P, K and Ca per acre applied and their significance

Factor	Ch		Bl		Hr		Hk	
	b_i	$\underline{t}$	b_i	$\underline{t}$	b_i	$\underline{t}$	b_i	$\underline{t}$
b_o	0.34067	32.99**	0.34235	31.95**	0.31443	30.45**	0.31683	29.56**
P	0.06042	3.17**	0.04068	2.13*	0.06738	3.54**	0.05732	3.00**
K	-0.01502	1.58+	-0.01546	1.62+	-0.00592	0.62	-0.00567	0.60
Ca	-0.00023	0.25	0.00015	0.14	0.00066	0.73	0.00132	1.19
P^2	-0.00496	1.12	-0.00452	1.02	-0.00576	1.30	-0.00668	1.51+
K^2	0.00173	1.57+	0.00155	1.41+	0.00122	1.10	0.00095	0.86
PK	-0.00306	2.23*	-0.00140	0.86	-0.00446	3.26**	-0.00150	0.88
PKCa	-		0.00004	0.53	-		-0.00006	0.66
R^2	0.7081		0.6434		0.7395		0.6628	

Figure 3. Contours for the percent P in the leaves at the end of flowering derived from the prediction equation for the variety Chippewa at the Howard County Experimental Farm with P and K applied as variables and holding the Ca application constant at 0 lbs. per acre

——————— Limits of area investigated


0.34
0.36
0.38
800
600
400
200
K(lbs./acre)
0
100
200
P(lbs./acre)



38
0.40
0.42
0.44
0.46
0.48
0.50
200
300
400
P(lbs./acre)

Table 20. Analysis of variance for the percent K in the leaves sampled at the end of flowering at the Howard Experimental Farm

Source	Degrees of freedom	Mean squares	F
Main plots	61		
Replications	1	0.00515	< 1
Fertilizers (F)	30	0.86647	21.11**
Error a	30	0.04104	
Sub plots	186		
Varieties (V)	3	0.34031	11.12**
F x V	90	0.02237	< 1
Error b	93	0.03062	

Table 21. Partial regression coefficients relating the percent K in the leaves at the end of the flowering to fertilization and their significance

	Variety			
Factor	Ch	Bl	Hr	Hk
b_o	0.9286**	1.0046**	0.9891**	0.9963**
P	-0.0488	-0.0077	-0.0181	-0.0366
K	0.3124**	0.2861**	0.2101**	0.3801**
Ca	0.0446	0.0284	0.0109	-0.0166
P^2	0.0066+	0.0013	0.0027	0.0053+
K^2	-0.0221**	-0.0231**	-0.0139*	-0.0320**
Ca^2	-0.0005	0.0006	0.0003	0.0033
PK	-0.0023	-0.0002	0.0043	-0.0030
KCa	-0.0056+	0.0008	-0.0003	0.0006
PCa	-0.0058+	-0.0077*	-0.0036	-0.0023
PKCa	0.0005	0.0004	-0.0005	-0.0002
R^2	0.8042	0.8354	0.6849	0.8659

this is in contrast to the outcome of the test on the overall fertilizer x variety interaction in the analysis of variance.

In accordance with these results the following regression equation was fitted to the combined data:

$$\text{Percent K} = b_o + b_1P + b_{2Ch}\,K\,Ch + b_{2Bl}K\,Bl + b_{3Hr}K\,Hr + b_{4Hk}\,K\,Hk$$
$$+ b_3Ca + b_{11}P^2 + b_{22Ch}\,K^2\,Ch + b_{22Bl}K^2\,Bl + b_{22Hr}K^2\,Hr$$
$$+ b_{22}Hk\,K^2\,Hk + b_{23}\,KCa + b_{13}PCa.$$

The partial regression coefficients for this equation appear in Table 23. In this equation the partial regression coefficient for Ca reached the 0.05 level of significance, whereas it had no significance in the original equations. The coefficients for the P^2 and PCa terms reached a higher significance level than in the equations for the individual varieties. The coefficient for P estimated on the combined data for the varieties reached significance at the 0.20 level of probability.

Duncan's test on the coefficients for K and K^2 of Table 23 show differential responses at the 0.01 level of significance between Hk and Hr, and Bl and Hr with respect to K and K^2. Differences at the 0.05 level of probability occurred between Hk and Ch with respect to K and K^2 and between Hr and Ch with respect to K (Table 24). The prediction equations for the percent K in the leaves of each variety are given in Table 25.

The contours reproduced in Figures 4 and 5 show that the percent K in the leaves reached a maximum with varying rates of K at any level

Table 22. F tests on differential responses in percent K of the leaves among four varieties

Factor	Mean square	F
b_o	0.00284	< 1
P	0.00523	< 1
K	0.08376	2.74*
Ca	0.01168	< 1
P^2	0.00827	< 1
K^2	0.07814	2.55++
Ca^2	0.00377	< 1
PK	0.01998	< 1
KCa	0.01947	< 1
PCa	0.01106	< 1
PKCa	0.01619	< 1

Table 23. Partial regression coefficients, b_i, of the combined equation for percent K in the leaves of four varieties and their significance

Factor	b_i	_t_
b_o	0.9822	20.18**
P	-0.0331	1.57+
Ch x K	0.2826	11.84**
Bl x K	0.3208	13.44**
Hr x K	0.2231	9.35**
Hk x K	0.3458	14.49**
Ca	-0.0233	2.33*
P^2	0.0043	1.74++
Ch x K^2	-0.0209	6.68**
Bl x K^2	-0.0253	8.11**
Hr x K^2	-0.0144	4.60**
Hk x K^2	-0.0290	9.30**
KCa	-0.0009	< 1
PCa	-0.0043	2.81**
R^2	0.7908	

Table 24. Comparison of corresponding partial regression coefficients in the combined equation for the percent K in the leaves of four varieties using Duncan's multiple range test

Nature of differential response	Variety, regression coefficients and significance of differences[a]			
K	Hr	Ch	Bl	Hk
	0.2231	0.2826	0.3208	0.3458
K^2	Hk	Bl	Ch	Hr
	-0.0290	-0.0253	-0.0209	-0.0144

[a]Comparisons failing to reach the 0.05 level of significance are underlined with a solid line. In addition those reaching the 0.05 level but not the 0.01 level of significance are underlined with a broken line.

of P application. This is due to the highly significant linear and quadratic effects of K. The response to P shows a minimum over the range of application at any level of K. The effects are insignificant. Application of Ca would have a slight positive effect on the percent K but only up to the level of 115 lbs. of P per acre for the variety Hr and 265 lbs. of P per acre for the variety Hk.

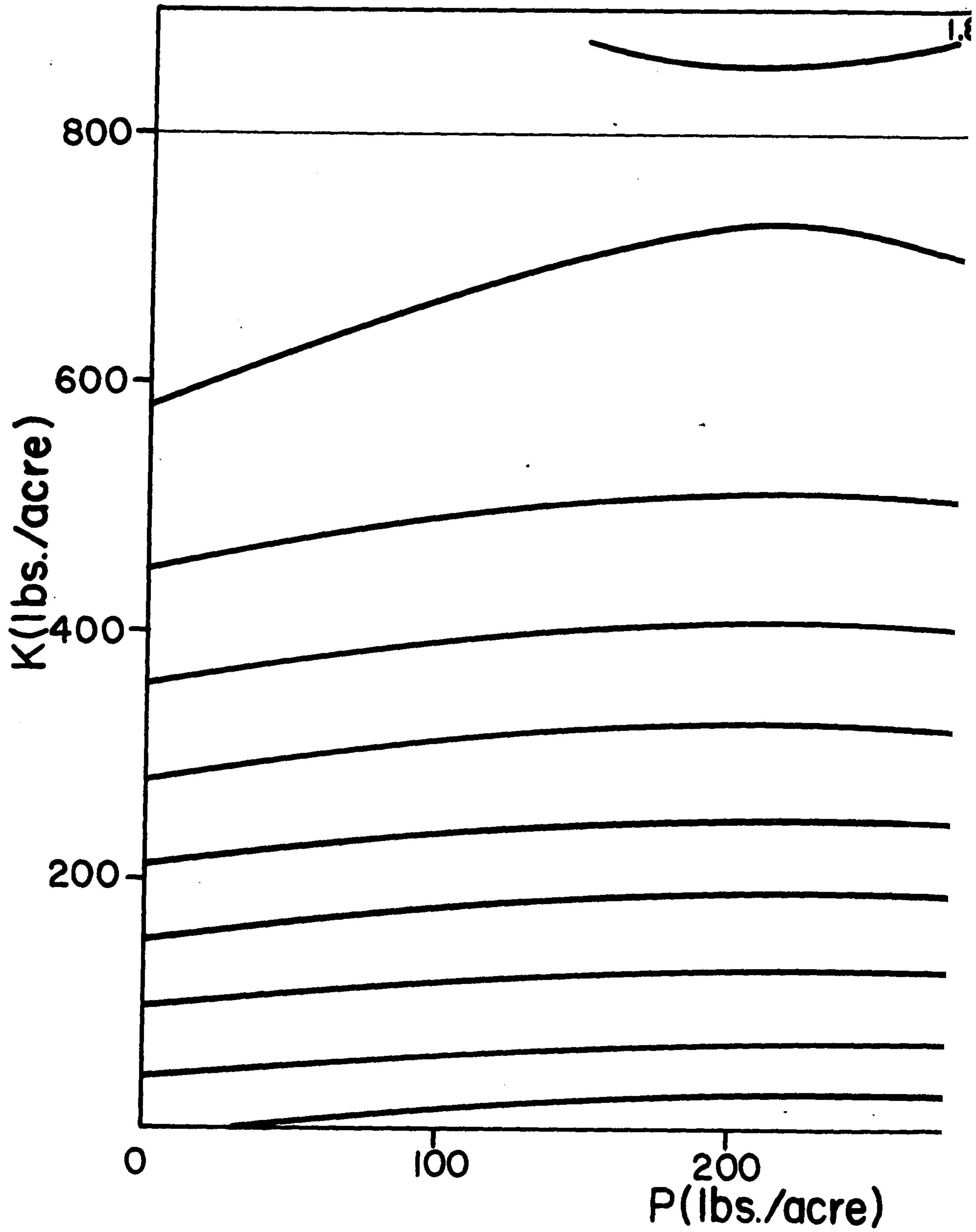
The strongest differential responses to K exist between Hr and Hk and are expressed in the graphs. When no K is applied the two varieties have about the same percent K content in the leaves but at almost any other point in the region of fertilization the variety Hk has a higher content than Hr. At a level of 250 lbs. of P per acre an application of 600 lbs. of K raises the K content of Hr by about 0.8% and that of

Table 25. Partial regression coefficients, b_i, of the equations for prediction of the percent K in the leaves at the end of flowering for individual varieties, expressed as percent K per 100 lbs. of P, K and Ca applied per acre and their significance

	Ch		Bl		Hr		Hk	
Factor	b_i	*t*	b_i	*t*	b_i	*t*	b_i	*t*
b_o	1.0271	12.12**	0.9579	11.31**	0.9611	11.34**	1.0448	13.33**
P	-0.1124	1.33	-0.0228	0.27	-0.0044	0.05	-0.1250	1.50+
K	0.2895	7.08**	0.2954	7.23**	0.2158	5.28**	0.3561	8.71**
Ca	0.0074	1.16	0.0147	2.31*	0.0050	0.78	0.0049	0.77
P^2	0.0256	1.30	0.0063	0.32	0.0111	0.56	0.0259	1.30
K^2	-0.0222	4.49**	-0.0229	4.62**	-0.0138	2.78**	-0.0307	6.21**
PCa	-0.0030	1.24	-0.0046	1.89++	-0.0043	1.75++	-0.0018	0.75
R^2	0.7950		0.8380		0.6782		0.8547	

Figure 4. Contours for the percent K in the leaves at the end of flowering derived from the prediction equation for the variety Harosoy at the Howard County Experimental Farm with applied P and K as variables and holding applied Ca constant at 1000 lbs. per acre

——————— Limits of area investigated


1.8
800
600
400
200
K(lbs./acre)
0
100
200
P(lbs./acre)

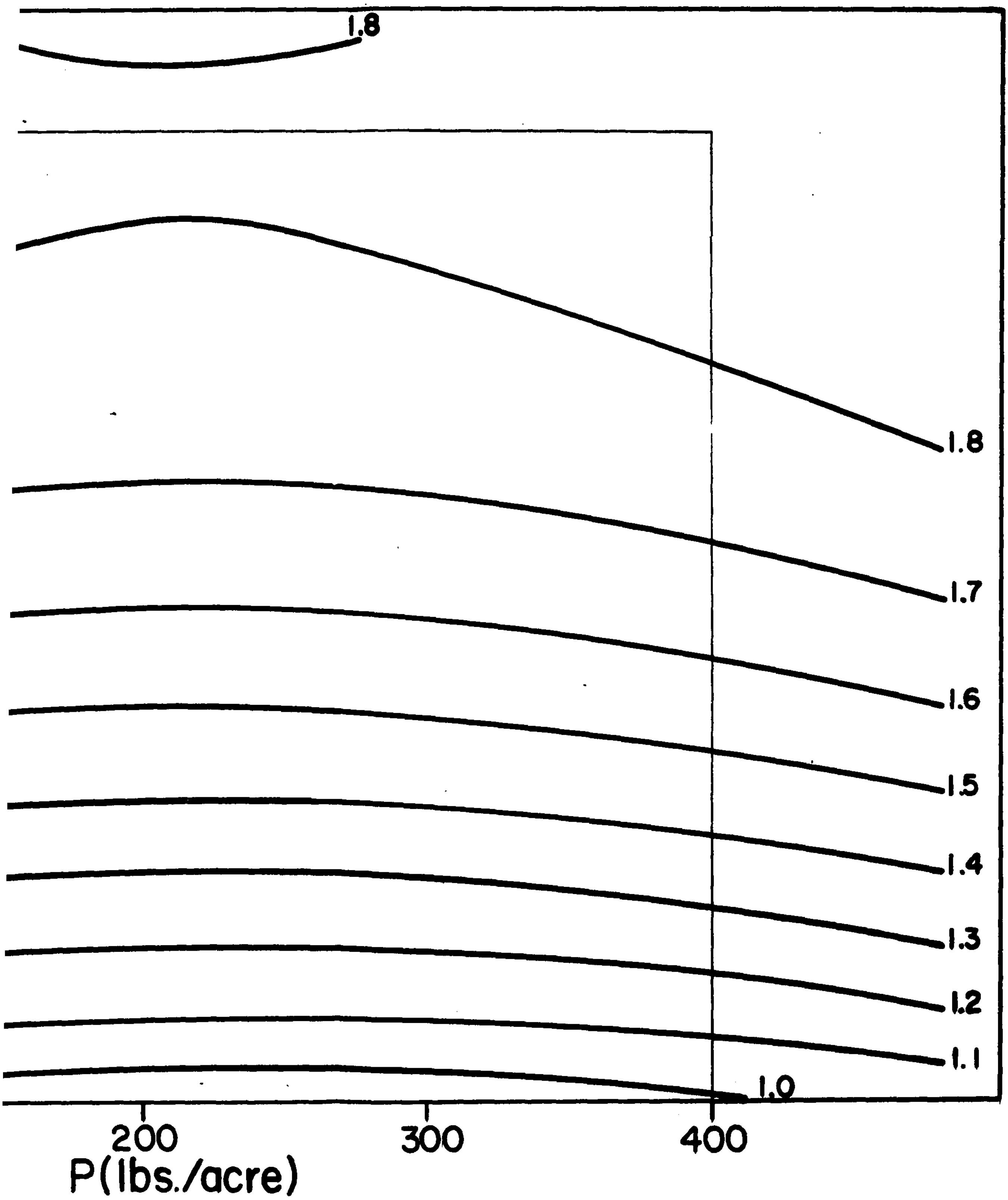
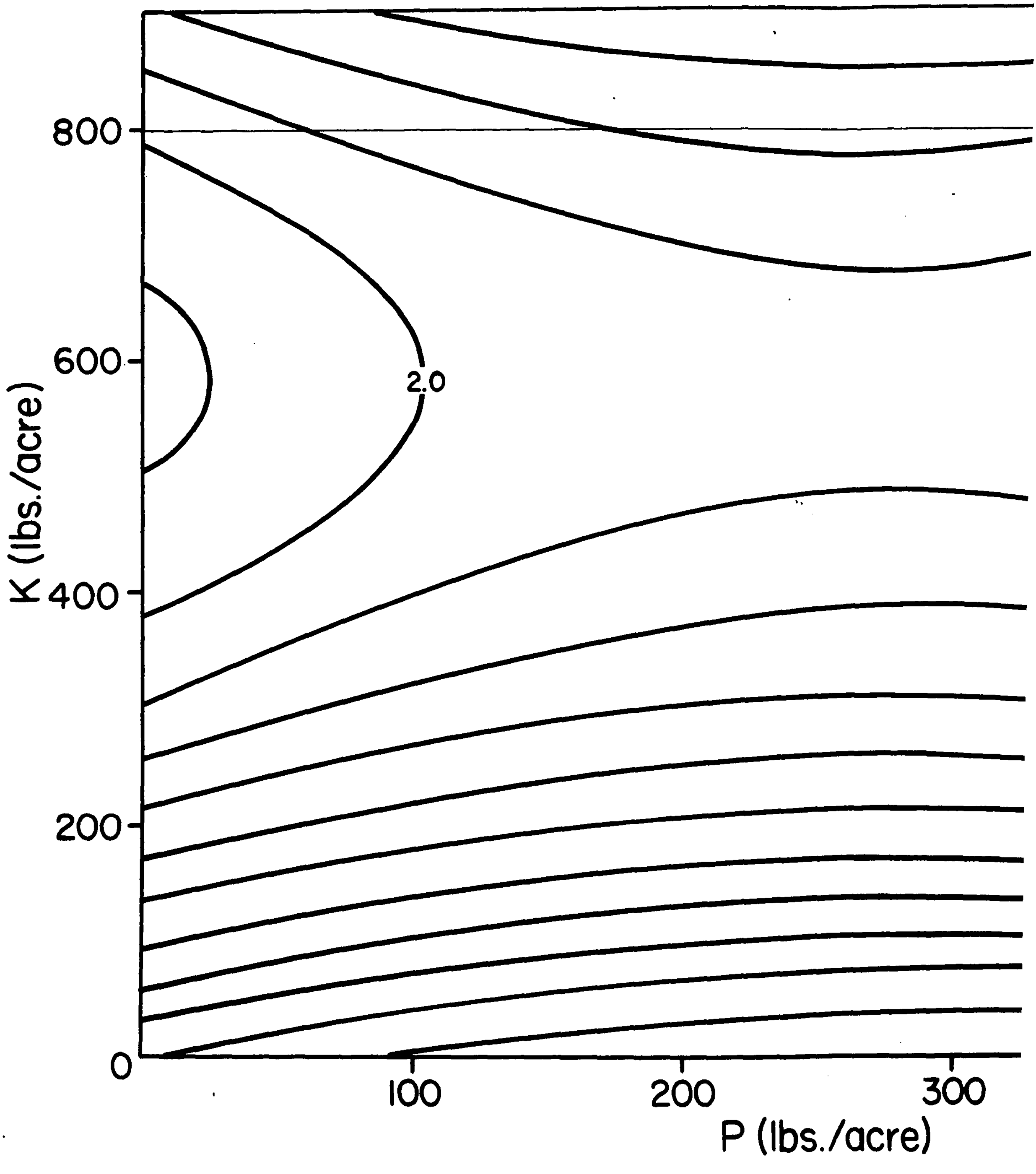
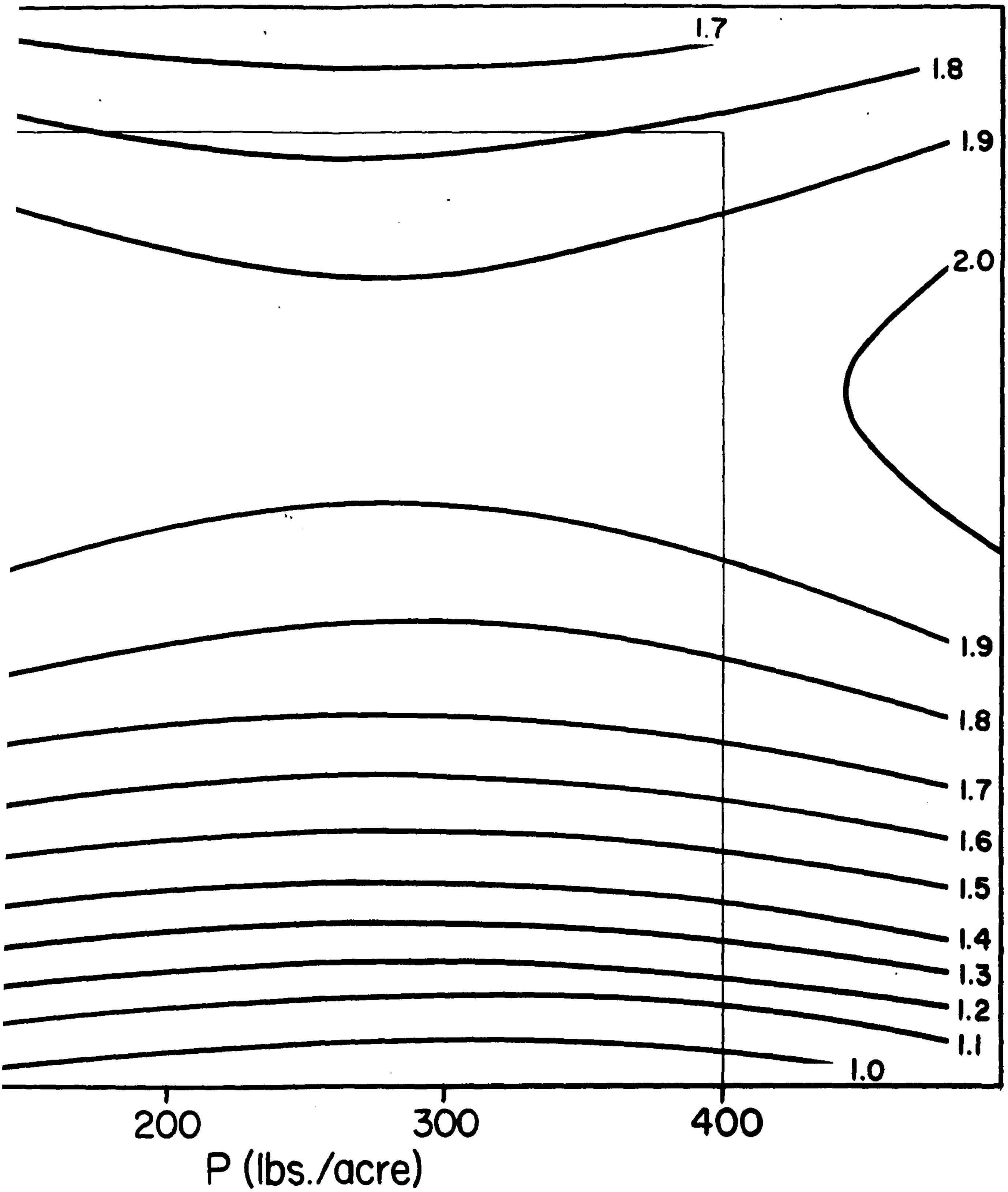

1.8
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
200
300
400
P(lbs./acre)

Figure 5. Contours for the percent K in the leaves at the end of flowering derived from the prediction equation for the variety Hawkeye at the Howard County Experimental Farm with applied P and K as variables and holding applied Ca constant at 1000 lbs. per acre

——————— Limits of area investigated


800
600
400
200
0
K (lbs./acre)
2.0
100
200
300
P (lbs./acre)



1.7
1.8
1.9
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
200
300
400
P (lbs./acre)

Hk by 1.0%. The differential responses are small despite their high level of significance.

c. <u>Percent N in the leaves</u> The analysis of variance indicates a weak influence from the applied fertilizers on the percent N in the leaves, strong differences in varietal N content and the absence of differential responses to fertilizer factors (Table 26). The R^2 values

Table 26. Analysis of variance for the percent N in the leaves sampled at the end of flowering at the Howard County Experimental Farm

Source	Degrees of freedom		Mean squares	F
Main plots	61			
Replications		1	0.03825	< 1
Fertilizers (F)		30	0.09247	1.34+
Error a		30	0.06887	
Sub-plots	186			
Varieties (V)		3	0.34212	5.40**
F x V		90	0.04412	< 1
Error b		93	0.06333	

were low for the multiple regression equations shown in Table 27 and F-tests on the significance of regression showed that an insignificant amount of variation at the end of flowering had been accounted for by the regressions for the varieties Hr and Hk. F-values of 2.46 and 1.73 for the varieties Bl and Ch were significant at the 0.05 and 0.25 level respectively. It is mainly the effects from P and Ca application and their interactions which reached significance at the 0.20 level or better

Table 27. Partial regression coefficients relating the percent N in the leaves at the end of flowering to fertilization and their significance

	Year and variety				
	1961				1963
Factor	Ch	Bl	Hr	Hk	Ch
b_o	5.0424**	5.2217**	5.0331*	4.7579**	5.3780**
P	-0.1114+	-0.1656**	-0.0140	-0.0236	-0.0317
K	-0.0752	-0.0094	-0.0226	0.0082	-0.0010
Ca	0.1312++	-0.0238	0.0403	0.1033*	-0.0092
P^2	0.0082	0.0133*	0.0013	0.0028	0.0007
K^2	0.0109+	0.0004	0.0037	0.0017	-0.0032
Ca^2	-0.0121+	0.0026	-0.0063	-0.0095++	-0.0019
PK	-0.0027	0.0031	-0.0067	-0.0024	-0.0012
KCa	-0.0041	0.0035	0.0029	-0.0055+	0.0072++
PCa	0.0064	0.0044	0.0038	-0.0034	0.0036
PKCa	0.0000	-0.0008	0.0003	0.0010+	0.0003
R^2	0.2535	0.3255	0.1255	0.1575	0.2925

and there is no conformity among the varieties in this respect.

The multiple correlation coefficients are low compared to those for the analysis of percent P and K and indicate that other factors which have not been considered exerted a more important influence on the percent N. One such factor may be identified from the 1963 data. The regression of the percent N in Ch on fertilizer input variables accounts for little more variation than in 1961 and none of the coefficients reached the 0.05 level of significance (Table 27). The regression of the percent N on soil fertility values on the other hand indicates a significant influence of soil pH. The linear and quadratic components of the pH effect as well as the pH x N_s and pH x K_s interactions reached significance at the 0.05 level of probability (Table 28). The effect of pH on the N content of soybean leaves is presumably an indirect one. Since the N supply of soybeans is largely dependent on nodulation the pH influence may possibly be one of control of the nodulation environment.

No differential responses in percent N in the leaves were identified by the F-tests shown in Table 29.

The following multiple regression equation

$$\text{Percent N} = b_o + b_1P + b_2K + b_3Ca + b_{11}P^2 + b_{22}K^2 + b_{33}Ca^2$$

$$+ b_{23}KCa + b_{123}PKCa$$

was fitted to the combined data for all varieties. The partial regression coefficients for the factors K, K^2, KCa and PKCa failed to reach the 0.20 level of significance. Deletion of these terms led to the equation given in Table 30. The value of R^2 for the equation is very low, but the F value of 5.64 for the test on the overall regression is more than sufficient for significance at the 0.01 probability level.

The dependence of the percent N in the leaves on the application of P and Ca was graphed from this equation which applies to all four varieties. Figure 6 shows that the effect of P on the percent N, although significant, is very small. The percent N decreases approximately 0.20% over the entire range of P application and increases about 0.15% under the influence of Ca application.

c. Percent Ca in the leaves The analysis of variance indicates highly significant fertilizer effects and varietal differences in Ca

Table 28. Partial regression coefficients, b_i, relating the percent N in the leaves at the end of flowering of Chippewa grown in 1963 to soil fertility factors and their significance

Factor	b_i
b_o	5.3296**
pH	0.2690*
N_s	0.0026
P_s	-0.0002
K_s	0.0008++
$(pH)^2$	-0.7691*
$(Ns)^2$	-0.0001
$(P_s)^2$	0.0000
$(K_s)^2$	0.0000
pHN_s	-0.0311*
pHP_s	0.0031
pHK_s	0.0026*
N_sP_s	-0.0001
N_sK_s	0.0000
P_sK_s	0.0000
R^2	0.4401

Table 29. F-tests on differential responses in percent N among four varieties

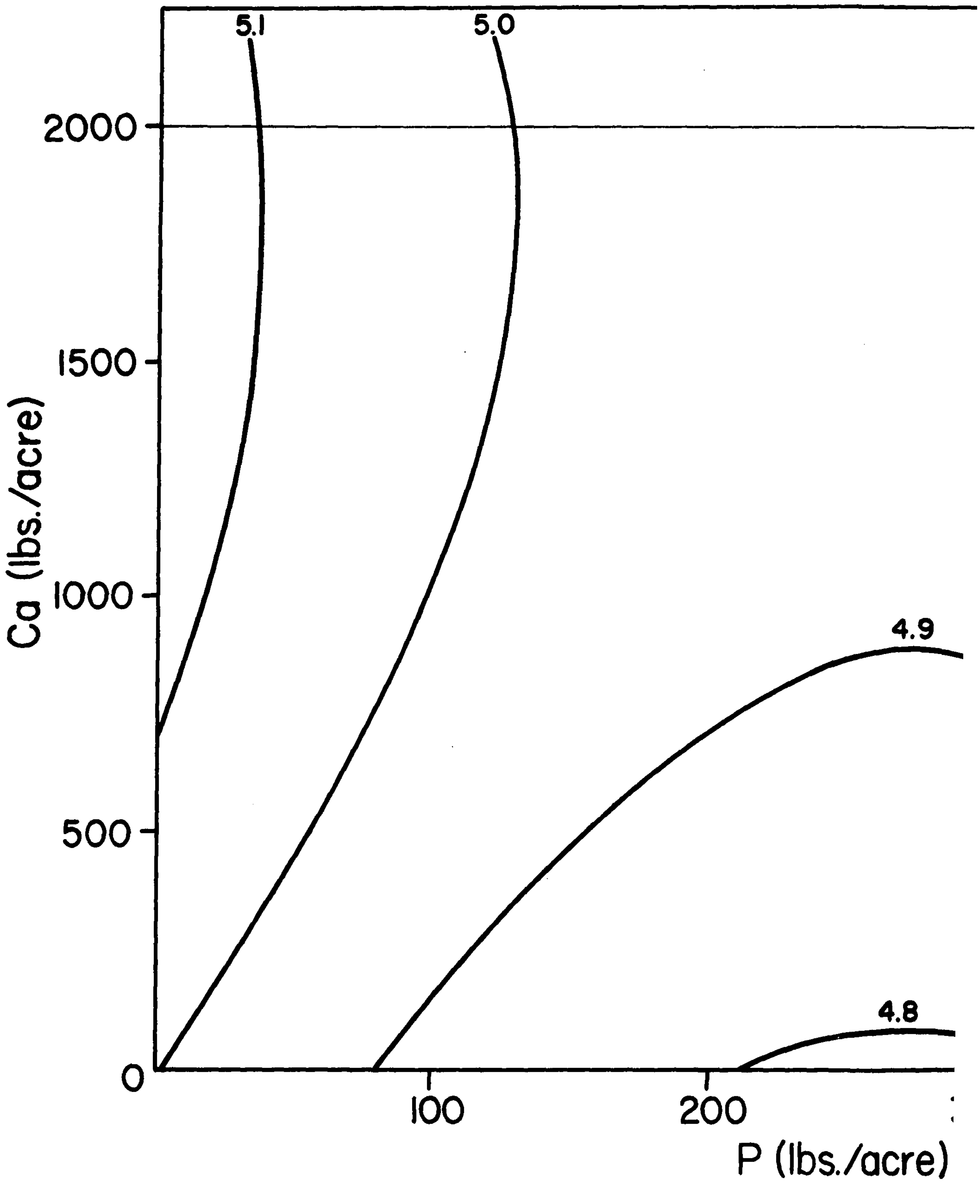
Factor	Mean squares	F
b_o	0.00780	< 1
P	0.08143	< 1
K	0.02187	< 1
Ca	0.08148	< 1
P^2	0.04290	< 1
K^2	0.03099	< 1
Ca^2	0.05795	< 1
PK	0.02993	< 1
KCa	0.04669	< 1
PCa	0.03502	< 1
PKCa	0.03521	< 1

Table 30. Partial regression coefficients, b_i, of the combined equation for the percent N in the leaves of four varieties and their significance

Factor	b_i	t
b_o	5.0077	99.40**
P	-0.0794	3.07**
Ca	0.0421	1.53+
P^2	0.0073	2.33*
Ca^2	-0.0029	1.01
R^2	0.0849	

Figure 6. Contours for the percent N in the leaves at the end of flowering derived from the prediction equation applying to all four varieties at the Howard County Experimental Farm with applied P and Ca as variables

——————— Limits of area investigated


5.1
5.0
4.9
4.8
2000
1500
1000
500
0
Ca (lbs./acre)
100
200
P (lbs./acre)

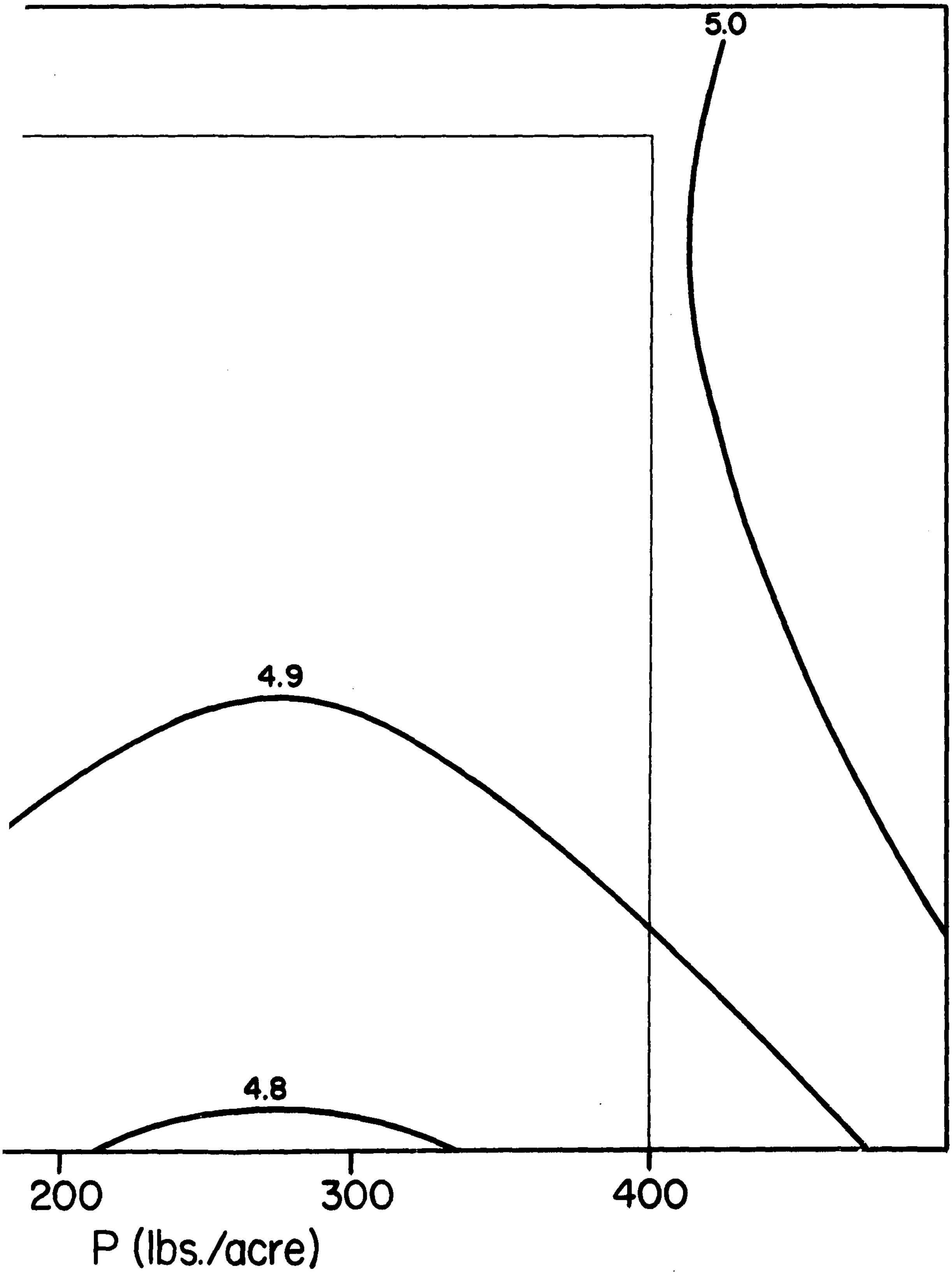

5.0
4.9
4.8
200
300
400
P (lbs./acre)

Table 31. Analysis of variance for the percent Ca in the leaves sampled at the end of flowering at the Howard County Experimental Farm

Source	Degrees of freedom		Mean squares	F
Main plots	61			
Replications		1	0.00848	< 1
Fertilizers (F)		30	0.19012	5.05**
Error a		30	0.03762	
Sub-plots	186			
Varieties (V)		3	0.59413	27.01**
F x V		90	0.02805	1.28+
Error b		93	0.02200	

content of the leaves.

Partial regression coefficients of the regression equations for the percent Ca in the leaves of the four varieties are given in Table 32. Ca application had no effect on the percent Ca. In the varieties Bl and Hk P and K fertilizers had a significant influence on the percent Ca; P in a positive and K in a negative direction. The percent Ca in the other two varieties was hardly effected by any of the treatments.

Similar effects have been reported by Nelson _et_ _al_. (1945). These authors found that K application lowered the percent Ca in the leaves and petioles of soybean plants very considerably. Other relevant relationships found in their study were a downward trend in the percent Mg in the leaves and petioles. This trend was weak since the percent Mg was already low. The percent P was also somewhat depressed by K application. This was also found in the present study (Figure 3).

Table 32. Partial regression coefficients relating the percent Ca in the leaves at the end of flowering to fertilization and their significance

Factor	Variety: Ch	B1	Hr	Hk
b_o	2.0500**	2.2512**	2.0737**	2.0168**
P	0.0411	0.0910*	0.0313	0.0939*
K	0.0139	-0.0768*	-0.0141	-0.1165**
Ca	0.0229	-0.0095	0.04667	0.0340
P^2	-0.0009	-0.0078+	0.0011	-0.0076
K^2	-0.0017	0.0055+	-0.0020	0.0106**
Ca^2	-0.0023	0.0001	-0.0046	-0.0023
PK	0.0009	-0.0031	-0.0015	-0.0012
KCa	-0.0032	-0.0014	0.0031	-0.0017
PCa	0.0051+	0.0055+	-0.0007	0.0013
PKCa	-0.0005	0.0000	0.0000	-0.0001
R^2	0.5991	0.6218	0.2829	0.5881

F-tests suggested that differential responses to K exist and almost reached the 0.05 level of significance (Table 33).

The partial regression coefficients for the combined equation are given in Table 34. The significance level of the factors involved changed very little.

$$\text{Percent Ca} = b_o + b_1P + b_{2Ch}K\ Ch + b_{2B1}K\ B1 + b_{2Hr}K\ Hr + b_{2Hk}K\ Hk + b_{3Ca} + b_{11}P^2 + b_{22Ch}K^2\ Ch + b_{22B1}K^2\ B1 + b_{22Hr}K^2\ Hr + b_{22Hk}K^2\ Hk + b_{13}PCa.$$

There was a suggestion of a K effect on the percent Ca in the leaves of the variety Hr. Duncan's multiple range test on the coefficients for K

Table 33. F-tests on differential responses in percent Ca among four varieties

Factor	Mean squares	F
b_o	0.02606	1.19
P	0.01652	< 1
K	0.05932	2.70++
Ca	0.00984	< 1
P^2	0.02984	1.36
K^2	0.05264	2.39++
Ca^2	0.00521	< 1
PK	0.00479	< 1
KCa	0.01567	< 1
PCa	0.01720	< 1
PKCa	0.00344	< 1

Table 34. Partial regression coefficients, b_i, of the combined equation for the percent Ca in the leaves of four varieties and their significance

Factor	b_i	$\underline{t}$
b_o	2.1474	59.82**
P	0.0692	3.42**
Ch x K	-0.0212	1.08
Bl x K	-0.0280	1.43+
Hr x K	-0.1250	1.79+
Hk x K	-0.1254	6.41**
Ca	0.0018	0.24
P^2	-0.0046	1.95++
Ch x K^2	-0.0001	0.03
Bl x K^2	-0.0010	0.39
Hr x K^2	0.0008	0.30
HK x K^2	0.0092	3.50**
PCa	0.0016	1.11
R^2	0.5157	

and K^2 of Table 34 indicated that Ca was highly significantly different from the other varieties with respect to K responses, and that Hk differed from the others with respect to the quadratic effect of K (Table 35). The prediction equations for the percent Ca in the leaves of individual varieties can now be fitted. The partial regression coefficients are shown in Table 36. P and K effects reached the 0.05 level of significance in nearly all cases. P^2 and K^2 were only of significance for the percent Ca in the variety Hk. The significant response of the variety Hk to P fertilization culminated in a maximum percent Ca at any level of K application, whereas the significantly curvilinear response to K caused a minimal Ca content in the leaves in the upper range of K applied at any rate of P application (Figure 7).

The strongest differential responses in percent Ca as a result of K fertilization occurred between the varieties Ch and Hk. As can be seen from Figures 7 and 8 the two varieties had practically the same Ca content when unfertilized. With higher rates of K and/or P application the difference in percent Ca between Ch and Hk increased with Ch having the highest content. The magnitude of the effect of 640 lbs. of K at 300 lbs. of P per acre is 0.1% for Ch and 0.4% for Hk, so that the differential effect is three times stronger than the response of Ch at this point in the investigated range. Even at this the differential responses between varieties are of small order.

e. <u>Percent Mg in the leaves</u> The analysis of variance in Table 37 indicates highly significant fertilizer and varietal effects on the percent Mg in the leaves and the absence of differential responses.

Table 35. Comparison of corresponding partial regression coefficients in the combined equation for the percent Ca in the leaves of four varieties using Duncan's multiple range test

Nature of differential response	Variety, regression coefficients and significance of differences[a]			
K	Hk -0.0212	Hr -0.0280	Bl -0.0350	Ch -0.1254
K^2	Bl -0.0010	Ch -0.0001	Hr 0.0008	Hk 0.0092

[a]Comparisons failing to reach the 0.05 level of significance are underlined with a solid line. In addition those reaching the 0.05 level but not the 0.01 level of significance are underlined with a broken line.

The multiple regressions presented in Table 38 for each variety show that the percent Mg was very strongly and curvilinearly affected by K in all varieties. The PCa interaction effect reached the 0.05 level of significance in two varieties: Bl and Hr. F-tests for differential responses (Table 39) reached the 0.25 level of significance in three cases, suggesting some possibility of difference in percent Mg in the leaves between varieties and differences in the linear and quadratic effects of Ca.

The following equation may now be written for the combined data:

Table 36. Partial regression coefficients, b_i, of the equations for prediction of the percent Ca in the leaves at the end of flowering for individual varieties expressed as percent Ca per 100 lbs. of P, K and Ca applied per acre and their significance

Factor	Ch		Bl		Hr		Hk	
	b_i	$\underline{t}$	b_i	$\underline{t}$	b_i	$\underline{t}$	b_i	$\underline{t}$
b_o	2.1113	39.70**	2.2470	42.26**	2.1518	40.47**	2.1109	38.63**
P	0.1534	2.49*	0.1405	2.28*	0.1160	1.91++	0.2038	2.60*
K	-0.0202	2.08*	-0.0510	5.25**	-0.0217	2.24*	-0.1230	3.14**
P^2	-0.0120	0.82	-0.0136	0.93	-0.0132	0.91	-0.0336	1.78++
K^2	-		-		-		0.0097	2.05*
R^2	0.5216		0.5432		0.2171		0.5576	

Table 37. Analysis of variance for the percent Mg in the leaves sampled at the end of flowering at the Howard County Experimental Farm

Source	Degrees of freedom		Mean squares	F
Main plots	61			
Replications		1	0.25658	13.36**
Fertilizers (F)		30	0.30307	15.79**
Error a		30	0.01920	
Sub-plots	186			
Varieties (V)		3	0.34972	56.32**
F x V		90	0.00658	1.06
Error b		93	0.00621	

$$\text{Percent Mg} = b_{oCh}Ch + b_{oBl}Bl + b_{oHr}Hr + b_{oHk}Hk + b_1P + b_2K$$

$$+ b_{3Ch}Ca\ Ch + b_{3Bl}Ca\ Bl + b_{3Hr}Ca\ Hr + b_{3Hk}Ca\ Hk$$

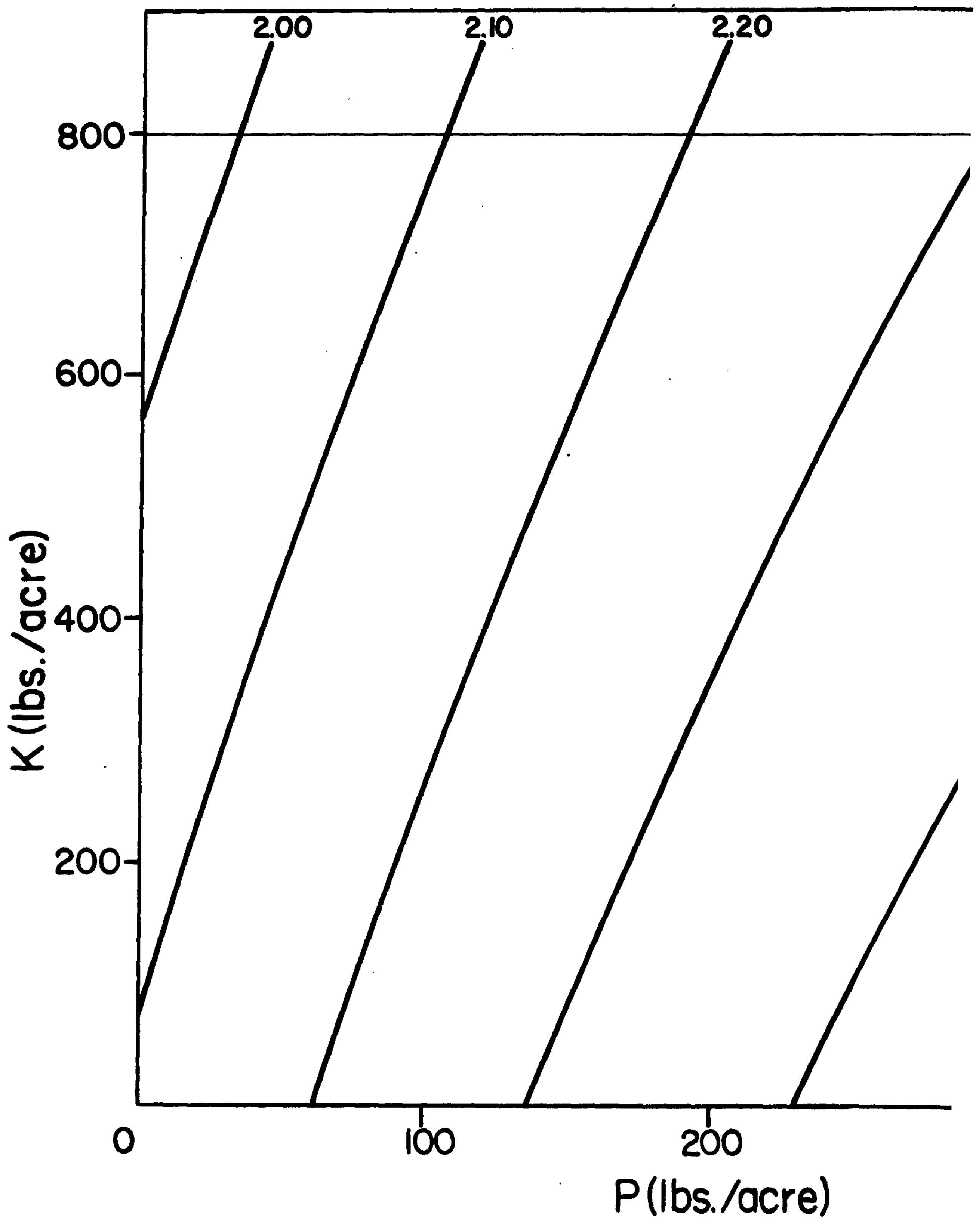
$$+ b_{22}K^2 + b_{33Ch}Ca^2\ Ch + b_{33Bl}Ca^2\ Bl + b_{33Hr}Ca^2\ Hr$$

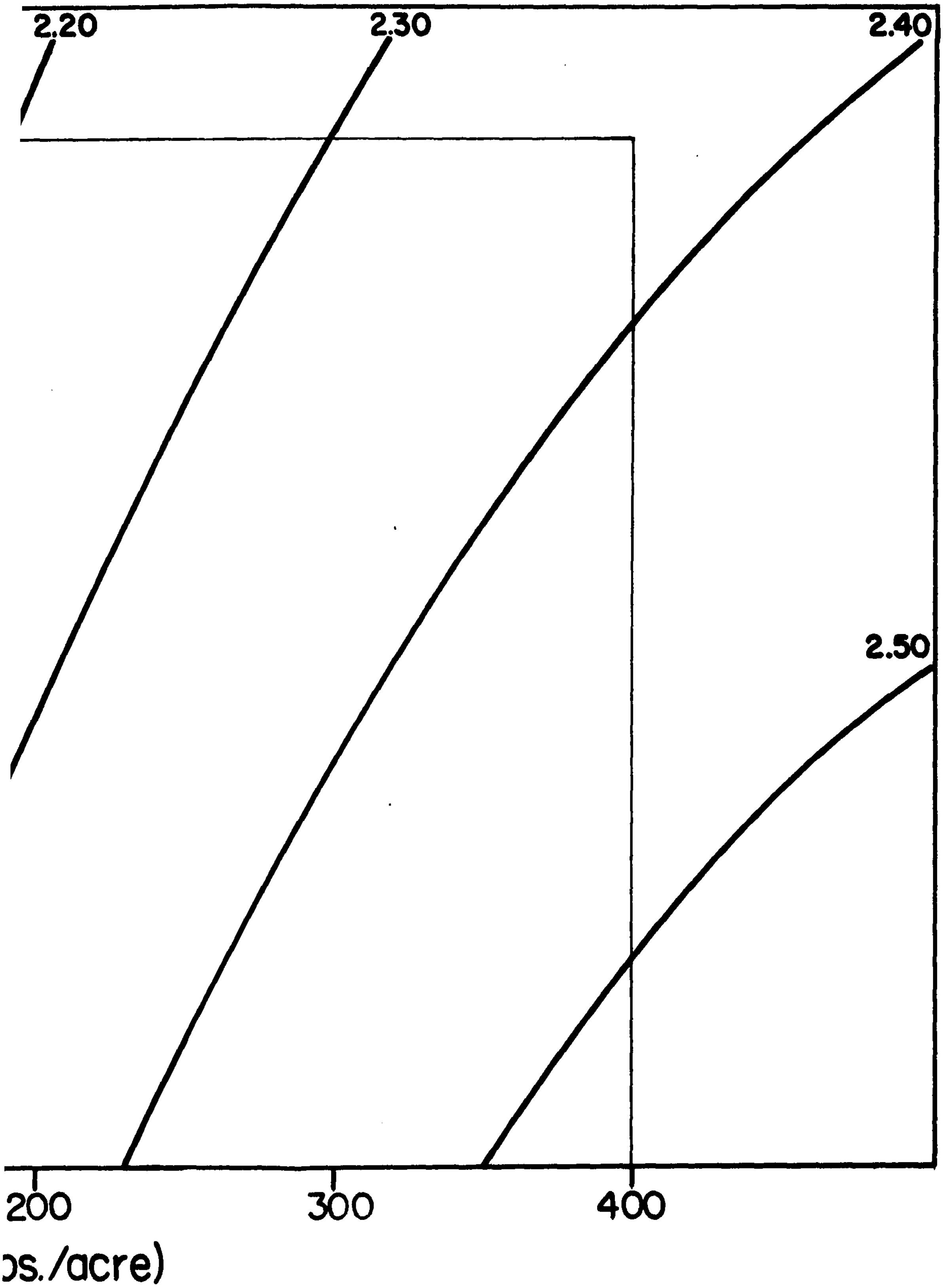
$$+ b_{33Hk}Ca^2\ Hk + b_{23}KCa + b_{13}PCa + b_{123}PKCa.$$

The partial regression coefficients resulting from fitting this combined equation are given in Table 40. In addition to the highly significant K and K^2 effects and the significant PCa interaction effect all varieties except Hk now showed Ca effects at the 0.01 or 0.05 level of significance. Duncan's test on the partial regression coefficients for Ca and Ca^2 indicates differential responses at the 0.01 level of significance between the varieties Hr versus Ch and Bl with respect to Ca and Ca^2. Ch differed from Hk in its linear and quadratic response to

Figure 7. Contours for the percent Ca in the leaves at the end of flowering derived from the prediction equation for the variety Hawkeye at the Howard County Experimental Farm with applied P and K as variables

——————— Limits of area investigated

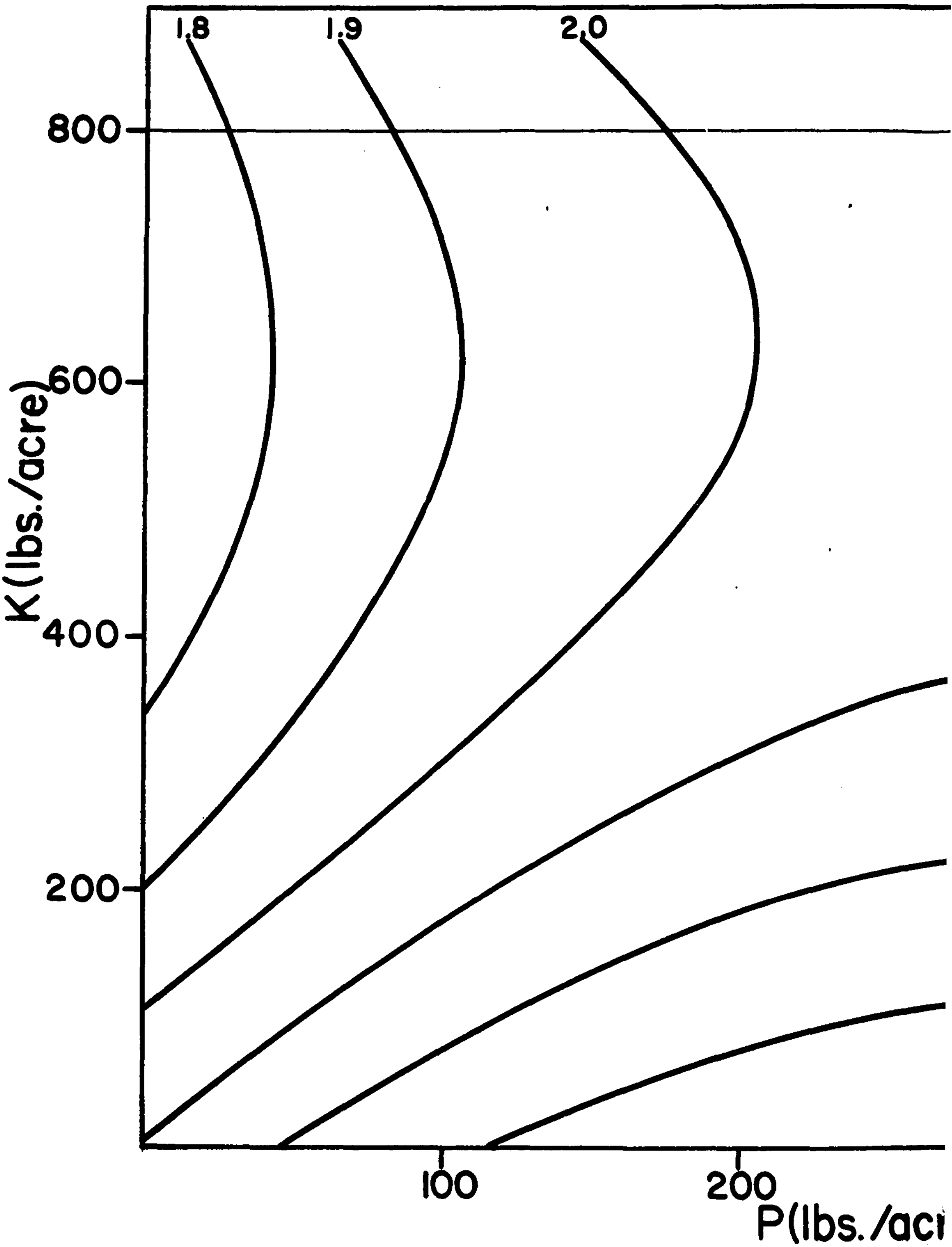

2.00
2.10
2.20
K (lbs./acre)
800
600
400
200
0
100
200
P (lbs./acre)

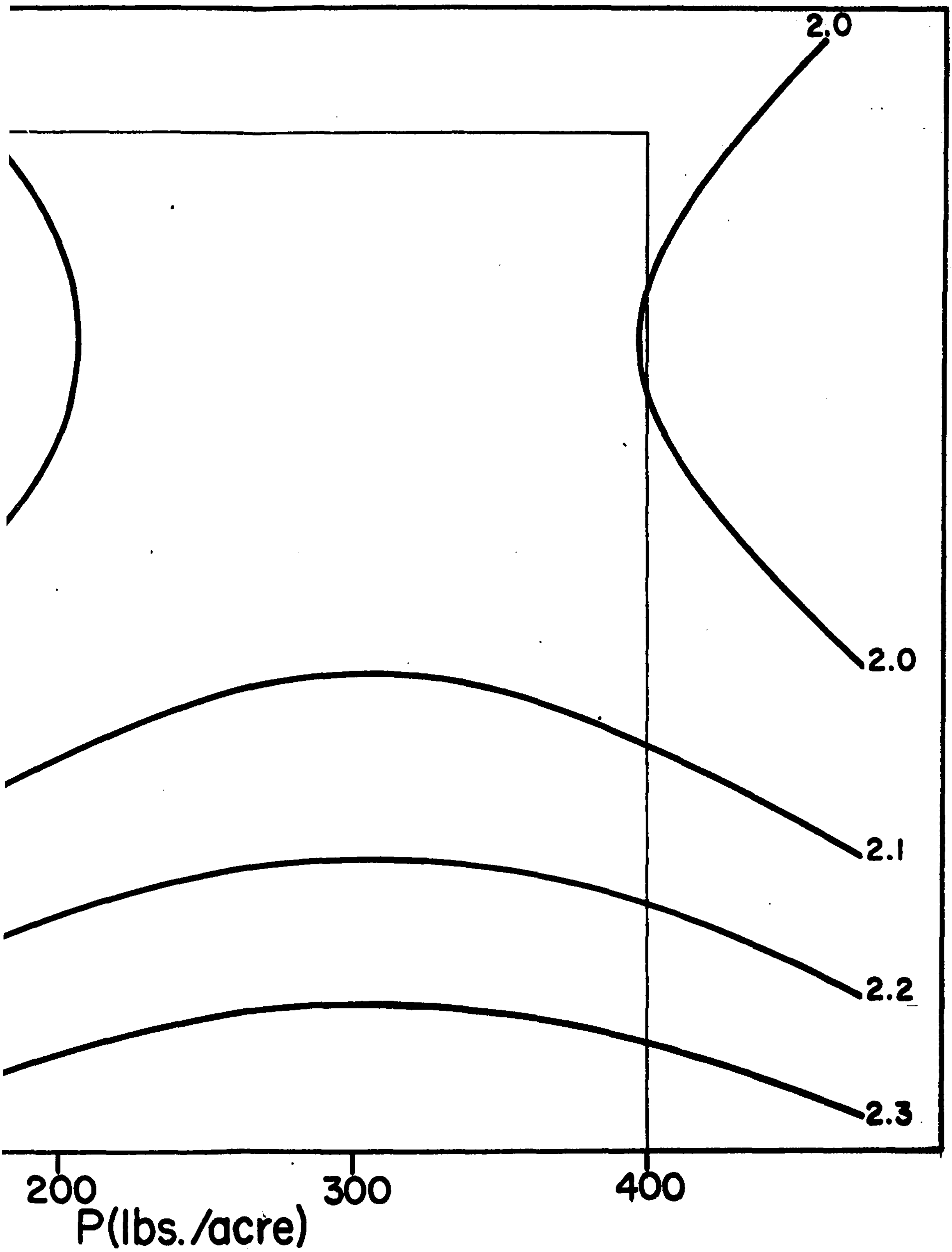


2.20
2.30
2.40
2.50
200
300
400
os./acre)

Figure 8. Contours for the percent Ca in the leaves at the end of flowering derived from the prediction equation for the variety Chippewa at the Howard County Experimental Farm with applied P and K as variables

——————— Limits of area investigated


1.8
1.9
2.0
800
600
400
200
K(lbs./acre)
100
200
P(lbs./ac



2.0
2.0
2.1
2.2
2.3
200
300
400
P(lbs./acre)

Table 38. Partial regression coefficients relating the percent Mg in the leaves at the end of flowering to fertilization and their significance

Factor	Variety			
	Ch	Bl	Hr	Hk
b_o	1.1295**	1.0839**	1.0793**	0.9548**
P	-0.0017	-0.0129	-0.0152	0.0137
K	-0.1969**	-0.1871**	-0.1715**	-0.1893**
Ca	-0.0260	-0.0350+	0.0120	0.0036
P^2	0.0010	0.0013	0.0018	-0.0007
K^2	0.0167**	0.0144**	0.0130**	0.0154**
Ca^2	0.0017	0.0009	-0.0039+	0.0009
PK	-0.0002	0.0005	0.0019	0.0000
KCa	0.0009	0.0036++	0.0037++	0.0011
PCa	0.0035+	0.0047*	0.0052*	0.0007
PKCa	-0.0003	-0.0005+	-0.0007++	-0.0001
R^2	0.8226	0.8647	0.7985	0.8699

Ca at the 0.05 level (Table 41). These differences were not obvious from the analysis of variance. Differences existed among the varieties when unfertilized. The Mg content of the leaves of Hk differed from that of Ch and Hr at the 0.01 level of probability, while Bl differed from Ch and Hk at the 0.05 level.

The dependence of the percent Mg in the leaves on fertilizer application can be predicted using the equations given in Table 42 for conditions similar to those of the experiment.

Figures 9 and 10 show the contours for the percent Mg in the leaves at the end of flowering as a function of K and Ca applied for the two varieties exhibiting the strongest differential responses to Ca. Whereas

Table 39. F-tests on differential responses in percent Mg among four varieties

Factor	Mean squares	F
b_o	0.01331	2.14+
P	0.00269	< 1
K	0.00193	< 1
Ca	0.00877	1.41+
P^2	0.00169	< 1
K^2	0.00348	< 1
Ca^2	0.00927	1.49+
PK	0.00164	< 1
KCa	0.00502	< 1
PCa	0.00772	1.24
PKCa	0.00455	< 1

Table 40. Partial regression coefficients of the combined equation for the percent Mg in the leaves of four varieties and their significance

Factor	b_i	t
Ch	1.1360	34.40**
Bl	1.0422	31.56**
Hr	1.0793	34.69**
Hk	0.9538	28.89**
P	0.0053	0.83
K	-0.1870	12.72**
Ch x Ca	-0.0433	3.00**
Bl x Ca	-0.0320	2.21**
Hr x Ca	0.0207	1.44+
Hk x Ca	0.0022	0.15
K^2	0.0152	9.04**
Ch x Ca^2	0.0033	2.12*
Bl x Ca^2	0.0017	1.09
Hr x Ca^2	-0.0039	2.51*
Hk x Ca^2	-0.0019	1.26
KCa	0.0021	1.57+
PCa	0.0032	2.34*
PKCa	-0.0003	1.86+
R^2	0.8439	

Table 41. Comparison of corresponding partial regression coefficients in the combined equation for the percent Mg in the leaves of four varieties

Nature of differential response	Variety, regression coefficients and significance of differences[a]			
Variety	Hk 0.9538	Bl 1.0422	Hr 1.0793	Ch 1.1360
Ca	Ch -0.0433	Bl -0.0320	Hk 0.0022	Hr 0.0207
Ca^2	Hk -0.0039	Hr -0.0019	Bl 0.0017	Ch 0.0033

[a]Comparisons failing to reach the 0.05 level of significance are underlined with a solid line. In addition those reaching the 0.05 level but not the 0.01 level of significance are underlined with a broken line.

the contours for the variety Ch are of an elliptic nature, those for Hr are hyperbolic. The Mg content is of the order of 1% when no K is applied and is strongly depressed by K application while it is hardly affected by Ca. The inverse relation between K application and percent Mg in plants has been well-known for many years (Beckenbach _et al._ 1938). The reason for the weak calcium effect presumably is that the reaction of the applied calcium carbonate with the soil takes longer than one season to develop.

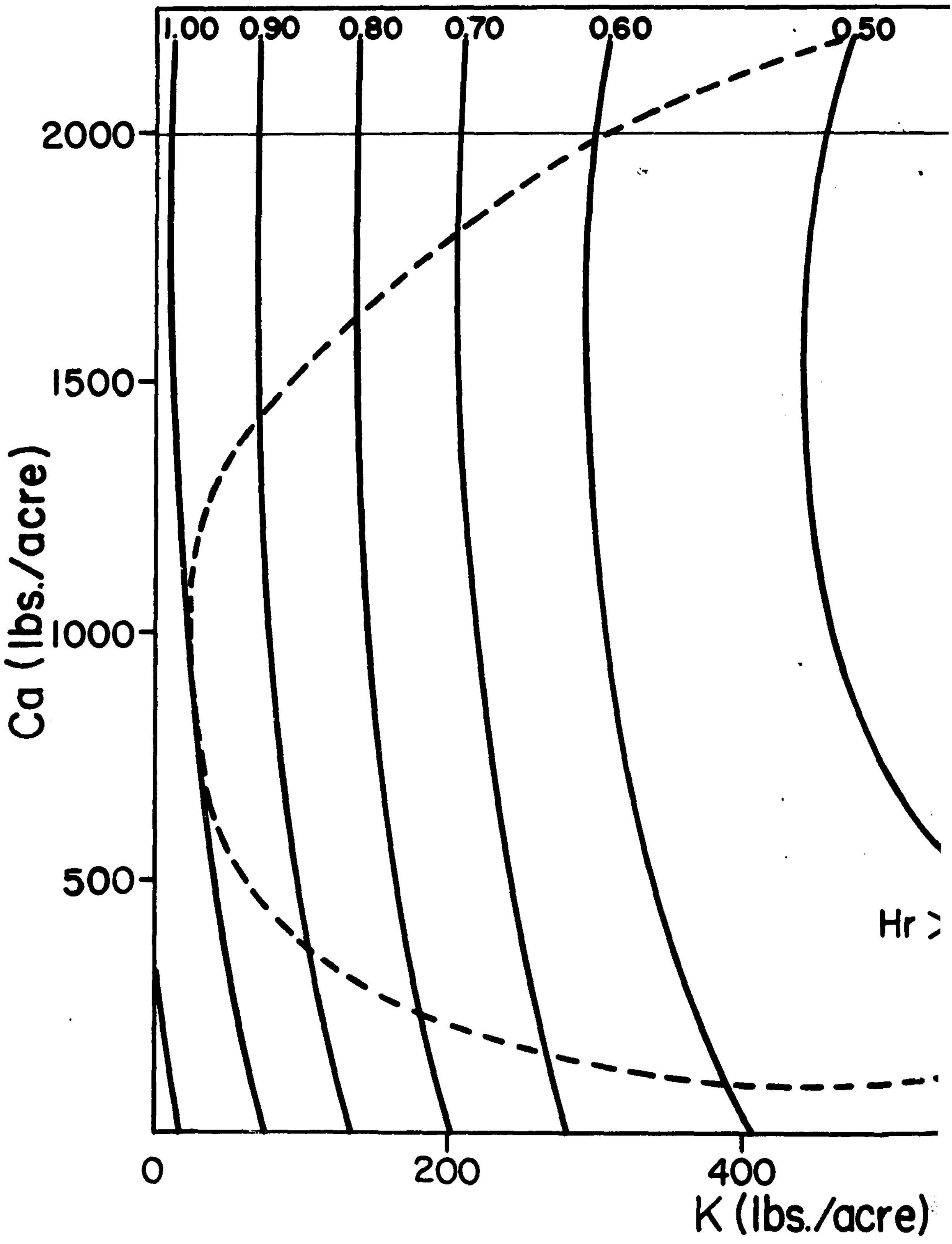
The projection of the line of intersection of the two Mg surfaces on the horizontal plane indicates that the variety Hr had a higher Mg

Table 42. Partial regression coefficients, b_i, of the equations for prediction of the percent Mg in the leaves at the end of flowering for individual varieties expressed as percent Mg per 100 lbs. of P, K and Ca applied per acre and their significance

Factor	Ch		Bl		Hr		Hk	
	b_i	$\underline{t}$	b_i	$\underline{t}$	b_i	$\underline{t}$	b_i	$\underline{t}$
b_o	1.1304	25.71**	1.0707	24.58**	1.0501	23.89**	0.9592	22.02**
P	0.0120	0.47	-0.0042	0.18	0.0149	0.58	0.0186	0.79
K	-0.2007	6.83**	-0.1968	8.19**	-0.1708	5.81**	-0.1813	7.54**
Ca	-0.0118	0.95	-0.0108	1.78	0.0038	0.31	-0.0012	0.20
K^2	0.0171	5.06**	0.0159	6.05**	0.0138	4.08**	0.0144	5.51**
Ca^2	0.0003	0.61	-	-	-0.0005	0.95	-	-
KCa	0.0004	0.35	0.0014	1.30	0.0011	1.08	0.0004	0.41
PCa	0.0028	1.28	0.0039	1.92++	0.0033	1.51+	0.0003	0.15
PKCa	-0.0003	0.91	-0.0003	1.21	-0.0004	1.27	-0.0001	0.34
R^2	0.8222		0.8625		0.7937		0.8688	

Figure 9. Contours for the percent Mg in the leaves at the end of flowering derived from the prediction equation for the variety Chippewa grown at the Howard County Experimental Farm with applied K and Ca as variables and holding applied P constant at 0 lbs. per acre

▬▬▬▬ (heavy solid line)	Contours
▬ ▬ ▬ ▬ (heavy dashed line)	Projected lines of intersection
—— (thin solid line)	Limits of area investigated


1.00
0.90
0.80
0.70
0.60
0.50
2000
1500
1000
500
Ca (lbs./acre)
0
200
400
K (lbs./acre)
Hr

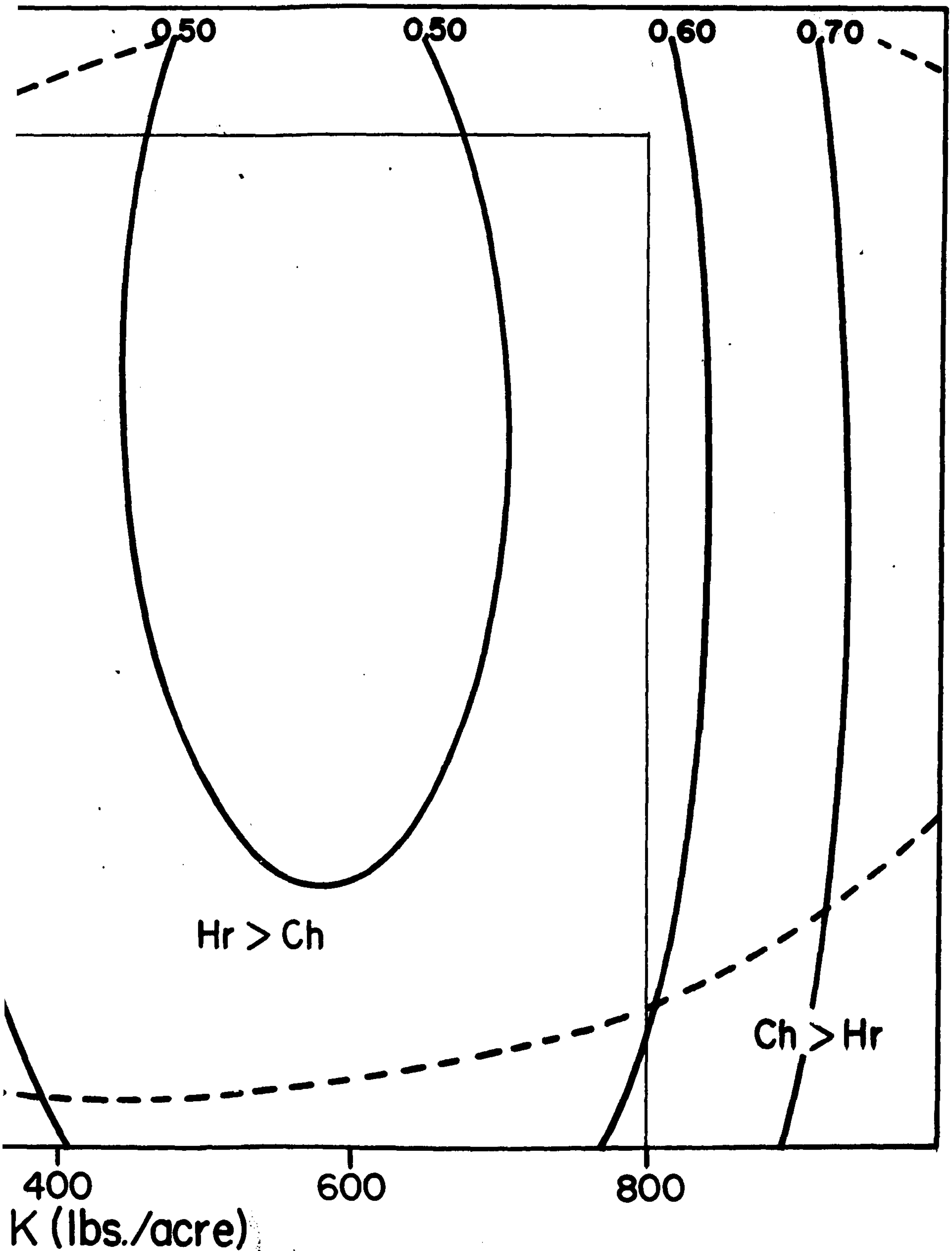
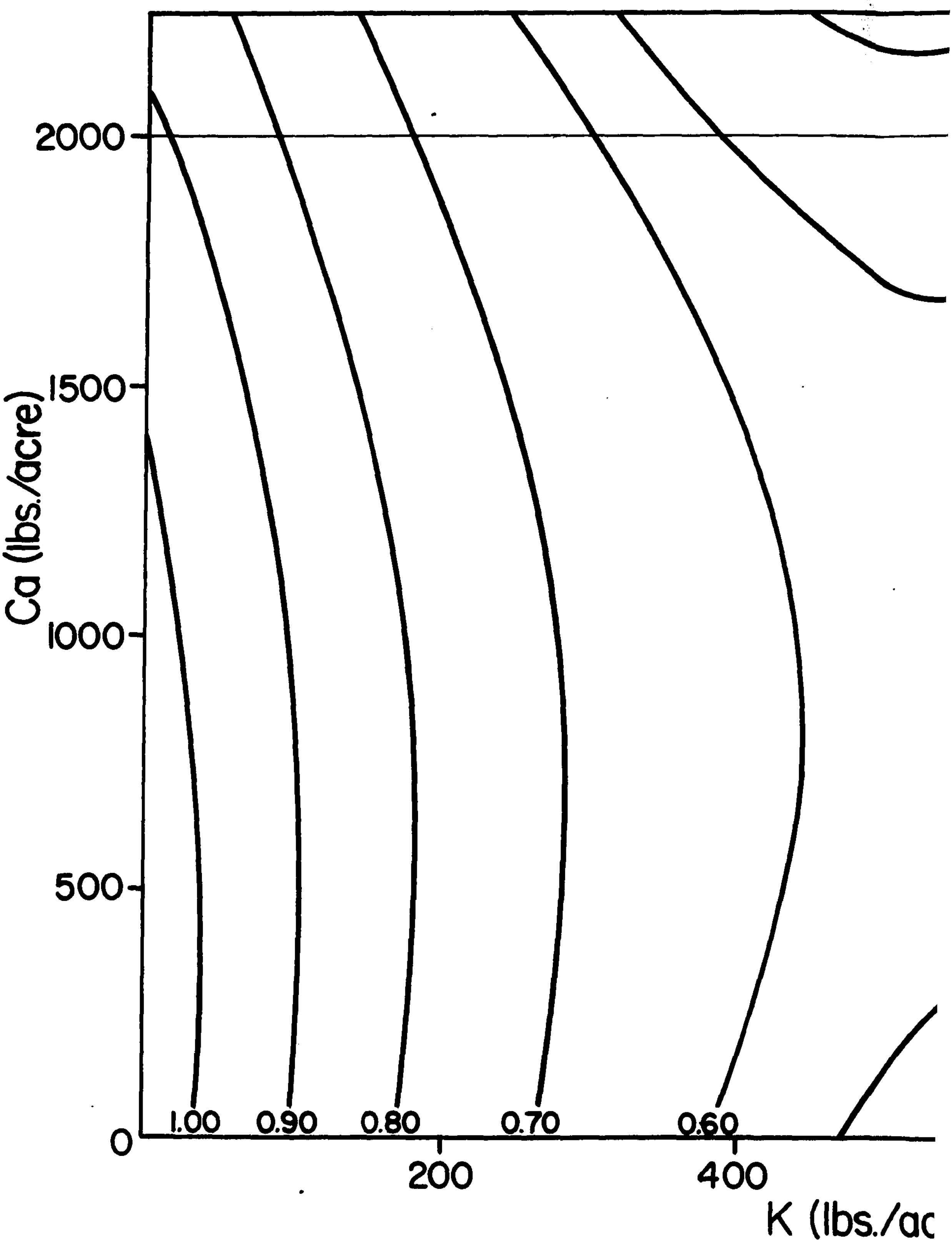
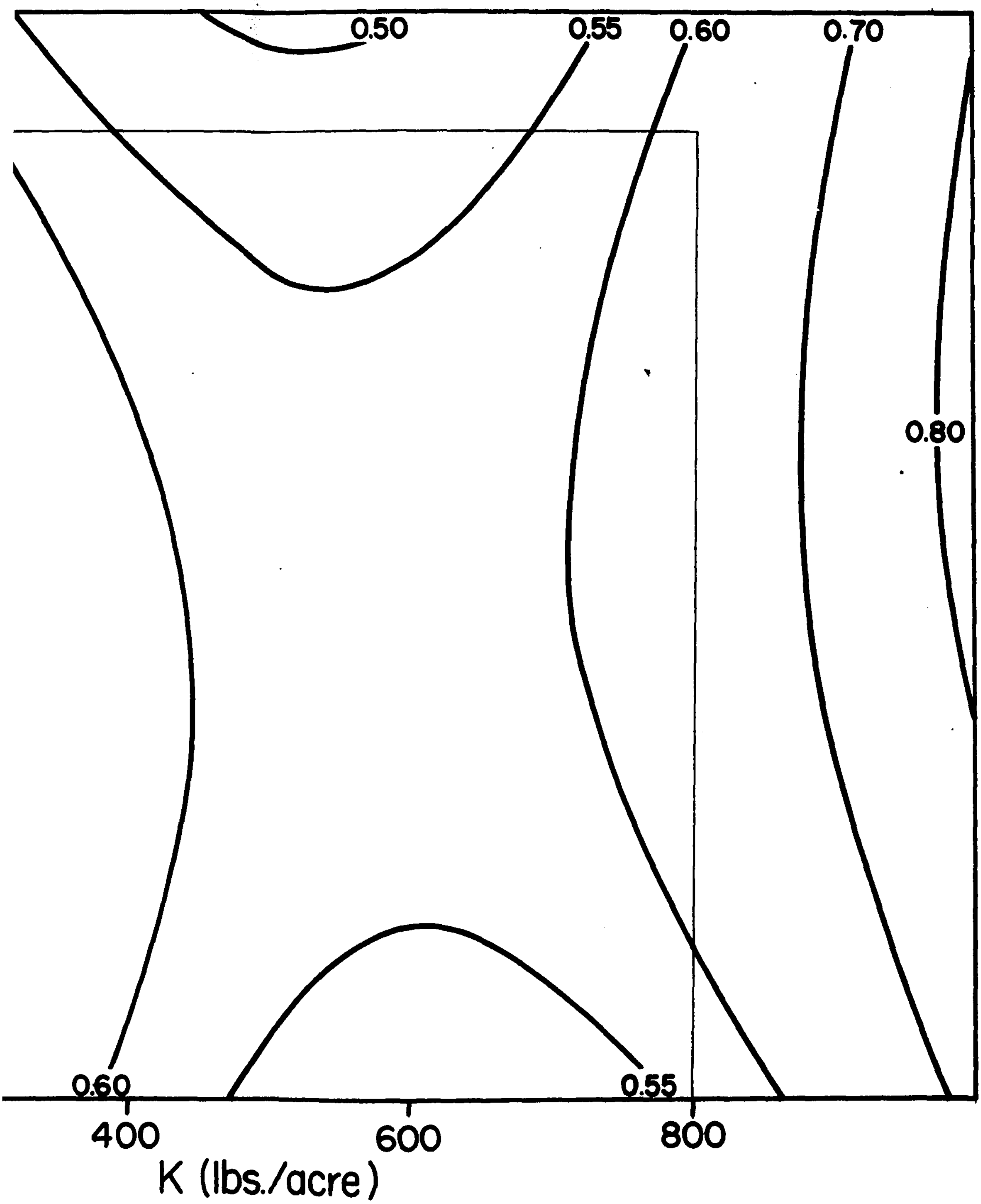

0.50
0.50
0.60
0.70
Hr > Ch
Ch > Hr
400
600
800
K (lbs./acre)

Figure 10. Contours for the percent Mg in the leaves at the end of flowering derived from the prediction equation for the variety Harosoy grown at the Howard County Experimental Farm with applied K and Ca as variables and holding applied P constant at 0 lbs. per acre

———————— Limits of area investigated


2000
1500
1000
500
0
Ca (lbs./acre)
1.00
0.90
0.80
0.70
0.60
200
400
K (lbs./ac



0.50
0.55
0.60
0.70
0.80
0.60
0.55
400
600
800
K (lbs./acre)

content than Ch over most of the region investigated due to varietal differences and differential responses to calcium.

4. Maturity date and degree of lodging as a function of fertilizer input variables

a. Maturity date Maturity date values were coded in the regression as of September 1. The analysis of variance indicates highly significant differences among the maturity dates of the varieties used and significant differential responses to fertilizer application (Table 43).

Table 43. Analysis of variance for maturity date of soybean plants grown at the Howard County Experimental Farm

Source	Degrees of freedom		Mean squares	F
Main plots	61			
Replications		1	204.1330	9.60**
Fertilizers (F)		30	17.5591	< 1
Error a		30	21.2747	
Sub-plots	186			
Varieties (V)		3	181.2406	6.43**
F x V		90	42.1877	1.50*
Error b		93	28.1951	

Analysis of the multiple regression equations for individual varieties indicated that several fertilizer effects reached significance at the 0.05 probability level. For the varieties Ch and Bl it was primarily the linear and quadratic effects of P and K which reached significance at various levels of probability. For Hk the linear and quadratic effects of P and Ca influenced the maturity date significantly, while none of the factors reached any significance for the variety Hr.

The residual mean squares for the four varieties varied widely as can be seen from Table 44. Bartlett's test indicates highly significant differences between these, i.e., $X^2 = 52.157$.

Table 44. Partial regression coefficients relating maturity dates of four varieties to nutrients applied, and their significance

Factor	Variety			
	Ch	Bl	Hr	Hk
b_o	27.3017**	28.4370**	27.7948**	25.9434**
P	2.4338+	1.4332++	-0.0755	-2.9797+
K	-3.4538*	-1.2156+	0.0453	0.1520
Ca	-0.6649	-0.2417	0.6977	3.0815+
P^2	-0.3678*	-0.2116*	0.0384	0.4079*
K^2	0.4356*	0.1528++	-0.0441	-0.0943
Ca^2	0.1073	0.0124	-0.1065	-0.4220*
PK	0.1841	0.1066+	-0.0179	-0.1517
KCa	-0.0911	-0.0159	0.0768	0.1682
PCa	0.1300	0.1179+	0.0201	0.0290
PKCa	-0.0249	-0.0212++	-0.0089	0.0038
R^2	0.2585	0.2643	0.1318	0.1810
Residual mean squares	38.8421	10.5066	12.0268	59.1234

The strong heterogeneity of variance interferes with F-tests for differential responses and combination of data for regression purposes without transformation of the observations.

b. Degree of lodging   Observations on the degree of lodging were expressed on a scale of 1 to 5. Perfectly erect plants were recorded as 1, while the value 5 indicated complete lodging.

The analysis of variance in Table 45 indicates highly significant fertilizer and variety effects as well as significant differential effects on lodging between varieties.

Table 45. Analysis of variance for the degree of lodging of soybean plants at maturity for four varieties grown at the Howard County Experimental Farm

Source	Degrees of freedom		Mean square	F
Main plots	61			
Replications		1	2.8317	12.07**
Fertilizers (F)		30	0.6302	2.69**
Error a		30	0.2347	
Sub-plots	186			
Varieties (V)		3	3.2353	63.29**
F x V		90	0.0755	1.48*
Error b		93	0.0511	

The multiple regressions for the degree of lodging of the individual varieties are shown in Table 46. The majority of the effects reaching significance at the 0.20 level of probability or higher involved the linear and quadratic components of K and the PK interaction. The variety B1 was an exception. The R^2 of the equation was very low and the F-test on the overall regression failed to reach the 0.25 level of

Table 46. Partial regression coefficients relating the degree of lodging at maturity for four varieties to nutrients applied, and their significance

Factor	Variety			
	Ch	Bl	Hr	Hk
b_o	1.0527**	1.2885**	1.1871**	1.2471**
P	0.0738+	-0.0144	0.1281	0.1024
K	0.0866++	0.0398	0.2960**	0.1715++
Ca	0.0040	0.0836	-0.0183	-0.0690
P^2	-0.0095	-0.0013	-0.0145+	-0.0119
K^2	-0.0082+	-0.0075	-0.0343**	-0.0213*
Ca^2	-0.0004	-0.0122+	0.0000	0.0052
PK	0.0069+	0.0112+	0.0195*	0.0114
KCa	0.0000	0.0027	0.0022	0.0049
PCa	0.0002	0.0076	0.0025	0.0029
PKCa	-0.0005	-0.0013	-0.0025+	-0.0011
R^2	0.4718	0.2190	0.5651	0.3546
Residual mean squares	0.0352	0.1158	0.1523	0.1456

significance. There was a suggestion that P might also affect the lodging of Ch by the fact that the P and P^2 effects reached the 0.20 and 0.10 levels of significance, respectively. Differential responses were not tested since Bartlett's test indicated highly significant heterogeneity of variance, i.e., X^2 = 28.4041**.

5. Yield of soybeans as a function of chemical composition of the leaves

It may be attempted to evaluate some of the natural relationships prevailing between the chemical composition of the leaves at the end of flowering and the yield of soybeans at maturity by means of the percentage composition determined for the five elements N, P, K, Ca and Mg. The resulting multiple regression equation for each variety is given in Table 47. Employed were the deviations from the means of the analytical values, their squares and some of the cross products. Although between 57 and 83 percent of the variation in yield can be explained by the variables chosen, few coefficients reached a significance level of 0.05 or higher.

In the variety Ch the percent N and percent Ca and three interaction terms involving either the percent N or percent Ca reached significance at the 0.05 probability level. The percent Mg, which was only influenced indirectly by varying the amounts of P, K and Ca, reached the 0.10 level of significance. So did its interactions with the percent P and the percent Ca in the leaves. None of the squared terms were of any consequence in any of the varieties. The fact that the percent K, which may be expected to be of utmost importance, did not reach any level of significance throws doubt on the value of the yield-composition relationships in the experiment.

F-tests on comparable coefficients between the varieties were run using the combined residual mean squares (Table 48). The expanded form of Williams' formula for the sum of deviations among corresponding partial regression coefficients was used in this case, since the corresponding elements of the inverse matrices are different for each multiple regression. Also, the coefficients must be weighted according to their variance when computing $\bar{b}_1$. Heterogeneity of variance was indicated, by Bartlett's test, which strictly renders combination of the four regressions invalid. The corrected χ^2 value (13.739) reached

Table 47. Partial regression coefficients relating the yield of soybeans to the percentage composition of the leaves at the end of flowering and their level of significance

Factor	Variety							
	Ch		Bl		Hr		Hk	
	b_i	t	b_i	t	b_i	t	b_i	t
b_o	36.1449	40.70**	37.1183	28.08**	41.6879	29.97**	30.8845	16.98**
%N	-4.4099	2.11*	-1.0514	<1	7.1702	1.49+	-7.6814	1.25
%P	-5.9022	<1	43.8664	1.52+	38.1099	1.16	66.5533	1.82++
%K	-2.7155	<1	5.3475	1.06	1.4249	<1	-8.2066	<1
%Ca	13.3873	2.92**	-2.5010	<1	3.1235	<1	-5.7169	<1
%Mg	-10.5935	1.84++	2.0983	<1	6.9007	<1	-33.2147	1.76++
$(\%N)^2$	3.4587	<1	1.9571	<1	10.3762	<1	7.9494	<1
$(\%P)^2$	71.5115	<1	347.8372	<1	-70.2172	<1	-32.6592	<1
$(\%K)^2$	2.0074	<1	3.6413	<1	-5.1573	<1	-0.0431	<1
$(\%Ca)^2$	7.0911	<1	13.6788	1.07	6.4487	<1	-0.3838	<1
$(\%Mg)^2$	2.6120	<1	68.9877	1.18	34.8983	<1	17.6408	<1
(%P) x (%K)	-78.8602	<1	-39.8990	<1	102.6488	<1	22.5981	<1
(%P) x (%Ca)	-252.1292	2.12*	-3.1930	<1	-56.5695	<1	239.7270	1.61+
(%P) x (%Mg)	-290.8960	1.94++	-294.9440	1.15	85.7590	<1	-144.3019	<1
(%K) x (%Ca)	24.3680	1.07	4.3512	<1	-47.1390	1.37+	-38.7344	1.36+
(%K) x (%Mg)	12.5262	<1	80.2514	1.11	58.1345	1.61+	26.6617	<1
(%Ca) x (%Mg)	66.1368	1.99++	-0.5867	<1	-64.8630	<1	-81.6651	1.53+
(%N)x (%P)	-195.0520	3.13**	49.8349	<1	-90.2942	<1	58.1048	<1
(%N) x (Ca)	38.5380	2.63*	-7.1964	<1	6.9546	<1	-17.4954	<1
R^2	0.8307		0.7131		0.5762		0.6500	

Table 48. Differential effects of chemical composition on the yield of soybeans

Factor	Mean squares	F
b_o	169.3840	9.85**
%N	43.9968	2.56++
%P	18.4990	1.08
%K	12.8951	< 1
%Ca	30.8977	1.80+
%Mg	101.2077	5.88**
$(\%N)^2$	3.6645	< 1
$(\%P)^2$	3.2231	< 1
$(\%K)^2$	3.0434	< 1
$(\%Ca)^2$	1.8042	< 1
$(\%Mg)^2$	5.5748	< 1
(%P) x (%K)	7.6240	< 1
(%P) x (%Ca)	30.8987	1.80+
(%P) x (%Mg)	9.3148	< 1
(%K) x (%Ca)	26.3649	1.53+
(%K) x (%Mg)	14.6129	< 1
(%Ca) x (%Mg)	36.1161	2.10+
(%N) x (%P)	32.1762	1.87+
(%N) x (%Ca)	30.5052	1.77+

the 0.01 level of significance. It is of interest, however, to observe the very highly significant differential influence of the percent Mg on the yield of the four varieties. The differential influence of the percent N on yield nearly attained significance at the 0.05 level. This result should be considered with caution under the conditions. Weaker indications of differential influences at the 0.25 level showed with respect to the percent Ca and several interaction terms involving all five elements. Interesting is the absence of a differential response to the percent P. This may suggest that even two varieties like Ch and Bl which are widely separated with regard to sensitivity to P concentra-

tions in the soil solution, have a similar response to the percent P once this is present in the leaf tissue.

Yield isoquants for the two varieties Hr and Hk illustrate the largest difference in effect of the percent Mg and percent N on yield of soybeans among the four varieties. A direct relationship exists between the percent Mg in the leaf of the variety Hr and its yield (Figure 11). In contrast to this Hk displays an inverse relation between the percent Mg and yield of soybeans in the range of nutrient contents actually observed (Figure 12). Hr yields higher over most of the region of nutrient contents which may be expected to exist in the field. This is indicated by the projection of the line of intersection between the two surfaces on the horizontal plane.

No conclusions can be made from the discussion of these relationships since there is reason to doubt if the fitted equations reflect relationships actually existing in the field. Similar relationships will be further discussed in corresponding sections dealing with pot experiments.

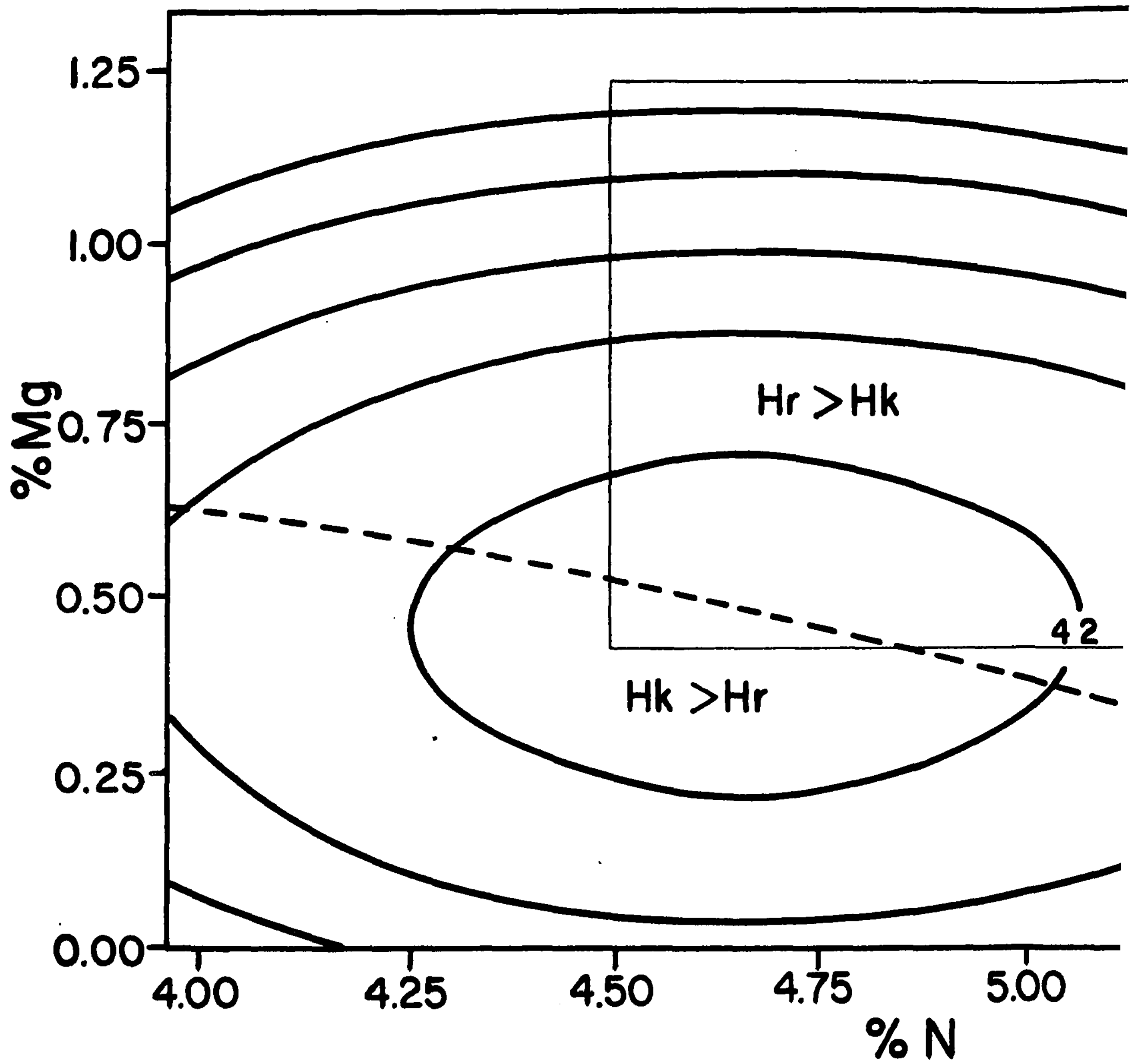
6. Conclusions

Multiple regression studies indicated highly significant yield responses to K application.

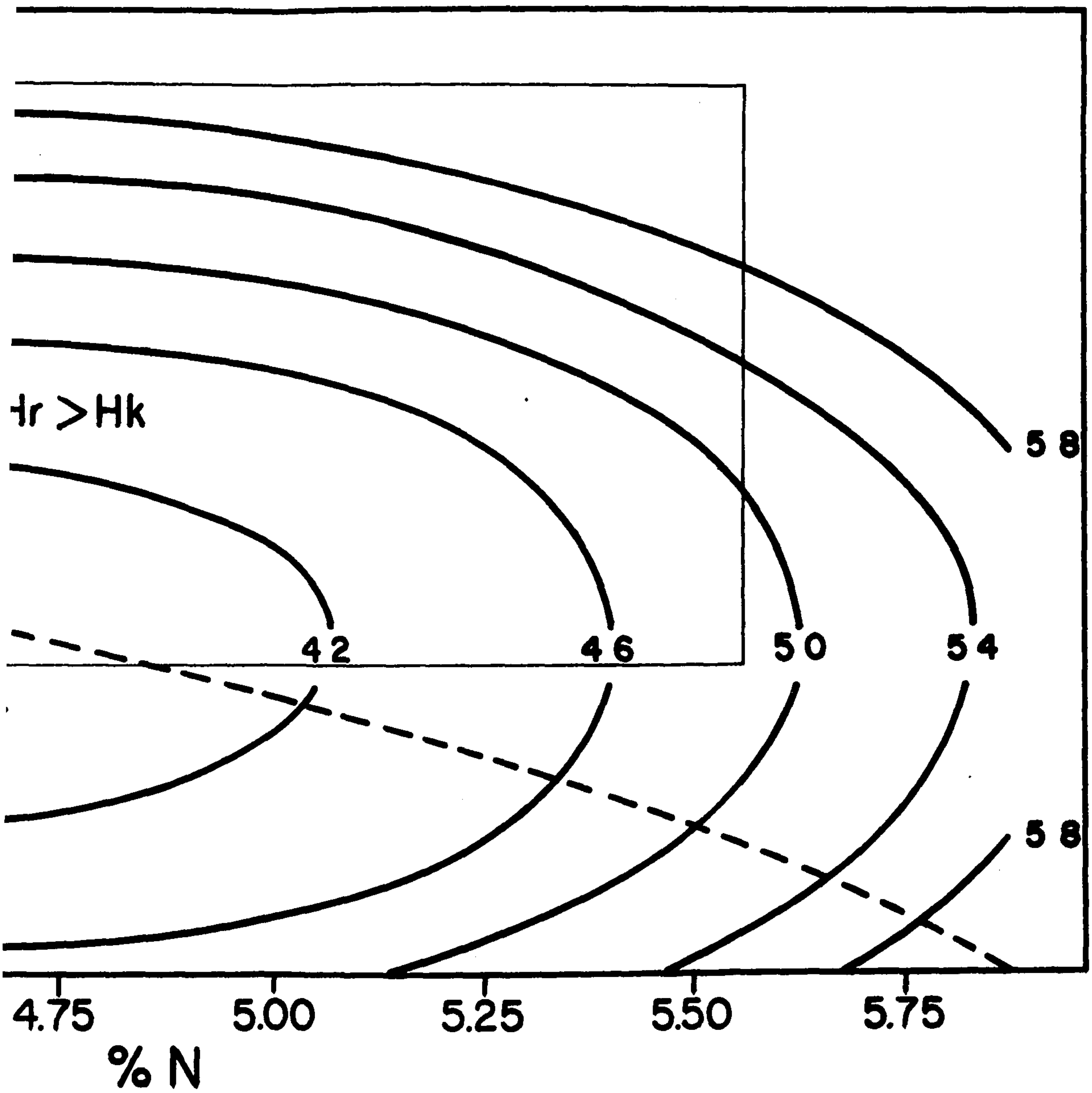
These responses were equally strong for all varieties compared. Their magnitude was of the order of four bushels for the first 100 lbs. of K per acre applied. P responses, if existing, were not sufficiently strong to reach significance under the conditions of the experiment.

Figure 11. Yield isoquants for the variety Hr grown at the Howard County Experimental Farm, expressed in bushels of soybeans per acre and with the percent Mg and percent N in the leaves as independent variables and holding the P content constant at 0.38%, K at 1.62% and Ca at 2.20%

——— (heavy line)	Isoquants
— — — —	Projected line of intersection
——— (thin line)	Limits of area investigated



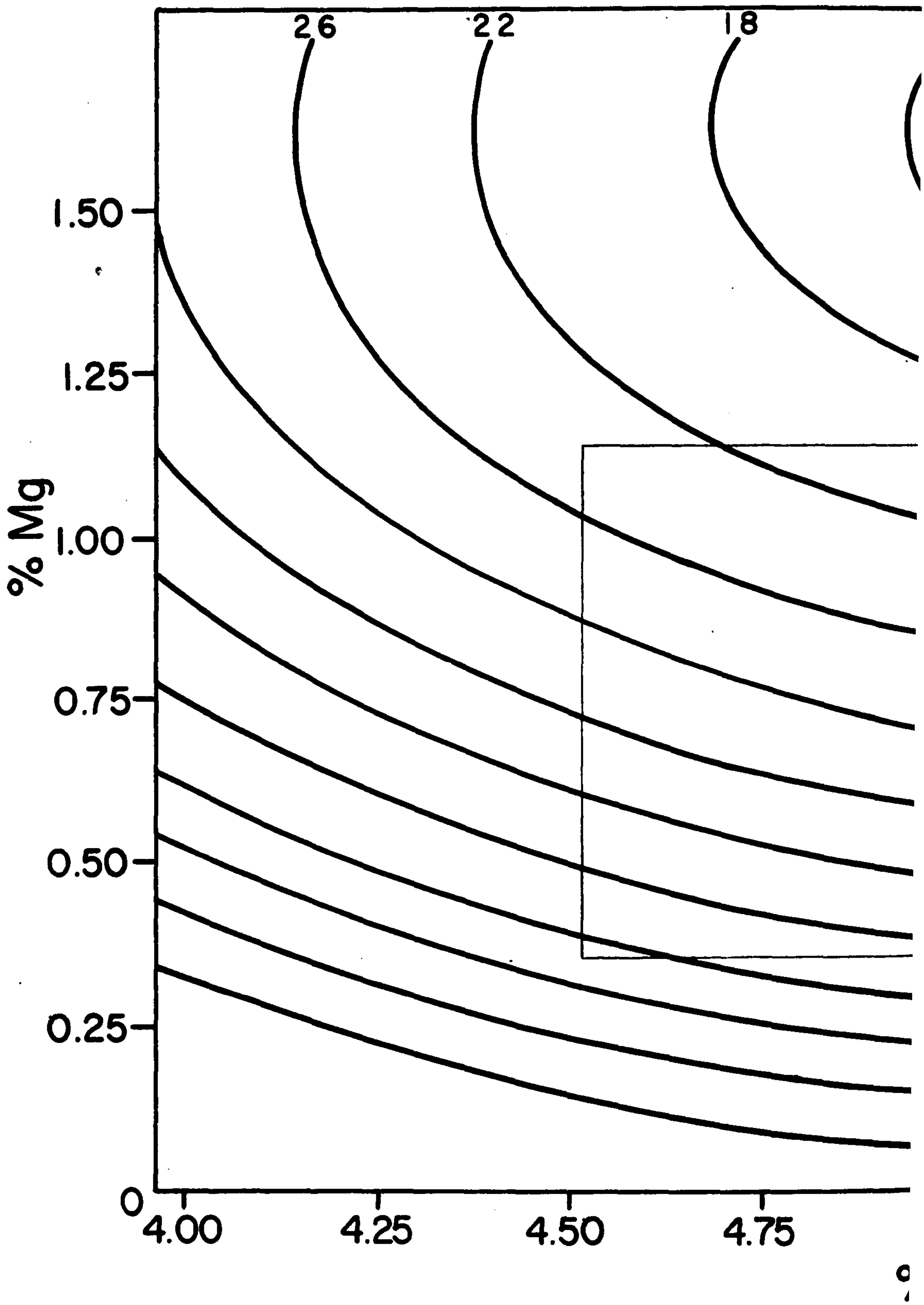
%Mg
1.25
1.00
0.75
0.50
0.25
0.00
4.00
4.25
4.50
4.75
5.00
% N
Hr >Hk
Hk >Hr
42



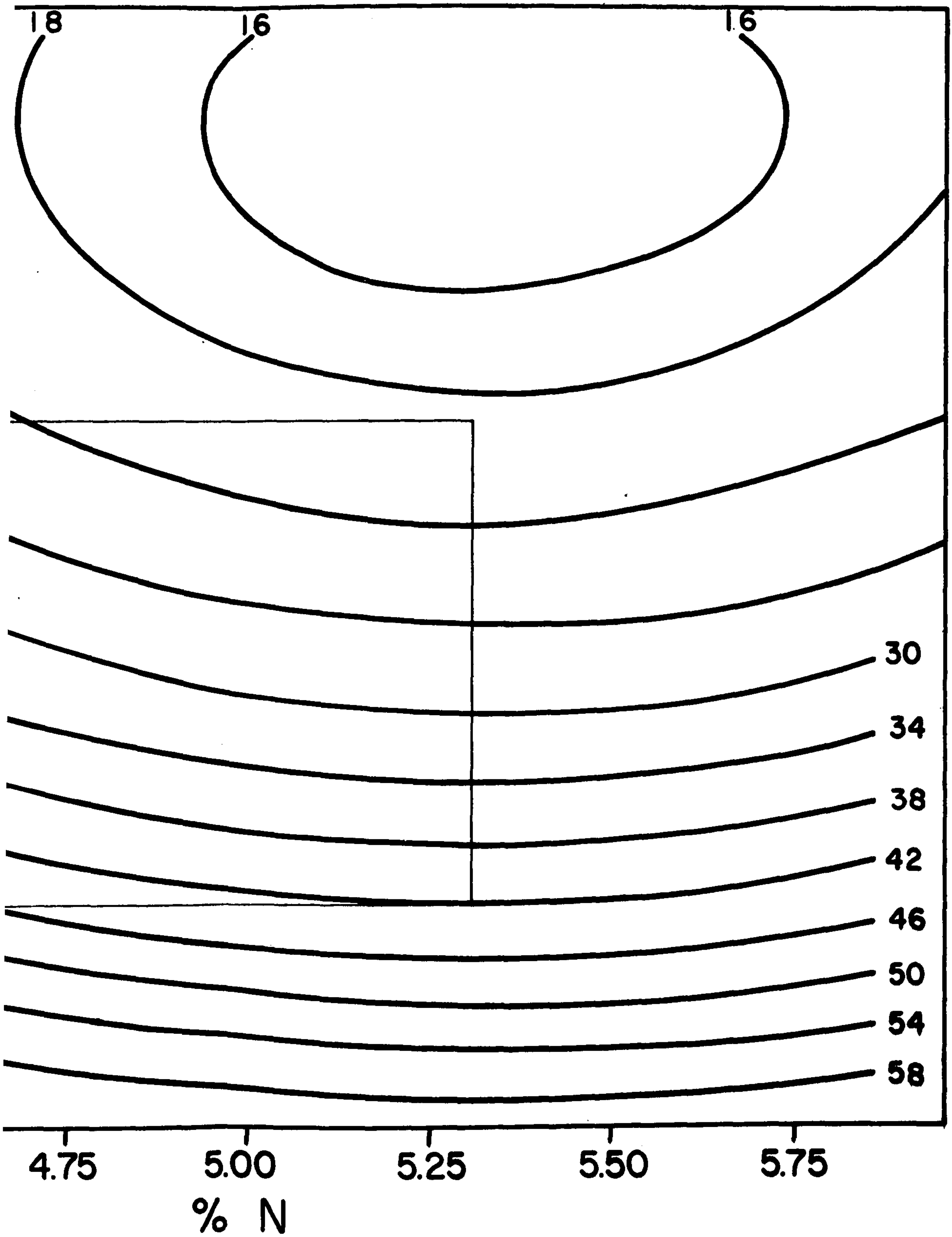
Hr > Hk
42
46
50
54
58
58
4.75
5.00
5.25
5.50
5.75
% N

Figure 12. Yield isoquants for the variety Hk grown at the Howard County Experimental Farm, expressed in bushels of soybeans per acre and with the percent Mg and percent N in the leaves as independent variables and holding the P content constant at 0.38%, K at 1.62% and Ca at 2.20%

———————— Limits of investigated area



26
22
18
% Mg
1.50
1.25
1.00
0.75
0.50
0.25
0
4.00
4.25
4.50
4.75



18
16
16
30
34
38
42
46
50
54
58
4.75
5.00
5.25
5.50
5.75
% N

Their magnitude may be estimated from graphical interpretation at up to three bushels in response to an application of 250 lbs. of P per acre. In many cases a negative response to P must be expected if less than 400 lbs. of K are applied due to a significant PK interaction effect. This, and the limited magnitude of the P and K responses in the field may explain some of the inconsistency experienced in yield responses of soybeans to fertilization if low rates of fertilization are employed, while soybeans grown at high natural fertility levels may yield considerably better than a crop grown in a less fertile field.

Differential responses to P fertilization occurred between the varieties and reached significance at the 0.05 level of probability. Their magnitude was small.

Yield prediction equations valid under the conditions of the experiment were used to compare optimum rates of fertilization between varieties. Maximum yields occurred at very high rates of fertilization which would not usually be applied in agriculture or be economical. The residual effect of fertilization was evaluated after two years. The effects of K and P were reduced, but the effect of liming was several times larger than in the year of application suggesting that the effects of liming take more than one season to develop fully.

Critical nutrient percentages and other characteristics related to optimum fertilizer combination for each of the varieties are given in a summary table (Table 49). The fertilizer combination for maximum yield of grain for each of the four varieties was interpreted from isoquant

Table 49. Fertilizer combination for maximum yield, critical nutrient percentages in the leaves at the end of flowering and predicted yield of soybeans at optimum fertilization and when unfertilized, in units of bushels per acre for four varieties grown at the Howard County Experimental Farm

Variety	Fertilizer combination for maximum yield		Critical nutrient percentage			$\hat{Y}$ check (bu./ac.)	$\hat{Y}$ max. (bu./ac.)	$\hat{Y}$ max. / $\hat{Y}$ check
	P	K	%P	%K	%Ca			
Ch	240	500	0.39	1.80	2.31	27	39	1.44
Bl	400[a]	580	0.36	1.91	2.30	29	40	1.38
Hr	400[a]	520	0.40	1.87	2.29	33	47	1.42
Hk	400[a]	540	0.40	1.99	2.01	27	39	1.44

[a]The limit of the investigated range is shown where the actual optimum rate exceeds the highest rate applied.

maps drawn from the yield prediction equations and are approximate values only. The critical nutrient percentages were calculated by substitution of the values of the fertilizer combination for maximum yield into the prediction equation for the appropriate nutrient and therefore represent the leaf composition at maximum expected yield. Others have used a somewhat different definition. Macy (1936) defined the critical nutrient percentage as the content at the transition from poverty adjustment to the luxury consumption region. Tyner (1946) interpreted it as that concentration above which doubtful or decreasing responses occur. The critical values for the Mg and N contents could not be calculated because the prediction equations for these nutrients contained several terms involving Ca. An approximate critical value of 5.0% may be assumed for N for all varieties from interpretation of Figure 6. The critical values for the percent P, K and Ca in the leaves at the end of flowering were remarkably similar for all varieties.

The chemical composition of the leaves at the end of flowering was significantly affected by fertilization. The percent P responded to P and K application to high levels of significance. A significant PK interaction effect existed also. The four varieties behaved similarly with respect to these factors. Raising the P content of the leaves by as little as 0.1 to 0.2% by means of P fertilization resulted in interveinal leaf discoloration symptoms if no K was applied. The symptoms appeared in plants which were to contain 0.44% P or more in the leaves at the end of flowering, combined with 1.11% K or less. The data allowed no conclusion as to the cause of the symptoms which may have been P toxicity or K deficiency.

The percent K was influenced by the linear and quadratic effects of K and also by the PCa interaction in the case of one variety. In an equation fitted to the combined data Ca effects also reached significance at the 0.05 level of probability. K application gave highly significant differential responses in percent K amongst the four varieties. These differences did not result in differential yield responses, however. The percent N could hardly be altered by fertilization, but responded significantly to the pH of the soil. When the data for four varieties were combined a highly significant negative P effect occurred which was, however, also of small magnitude. The percent Ca in the leaves of two varieties was increased by P and decreased by K application. Liming had no influence. The effect of K on the percent Ca was different among certain varieties at the 0.01 level of significance. The percent Mg showed a strong curvilinear response to K. In the range of practical significance the percent Mg was reduced by K application. The effect of liming was significant for all varieties except Hk when the data were combined. Differential responses due to Ca also existed.

Table 50 summarizes the magnitude of changes in nutrient composition of the leaves in response to the most significant fertilizer factors. The changes in percent K and percent Mg under the influence of 400 lbs. of K were among the largest. The differential effects were rather small considering that the varieties shown where the most contrasting according to Duncan's multiple range test.

The percentages N, Ca and Mg and their interactions with other elements reached some significance when relating the yield of soybeans

Table 50. Magnitude of responses and differential responses in nutrient content of the leaves at the end of flowering under the influence of P, K and Ca fertilization, involving one or more significant effects

Dependent variable	Variety	Factor specification P	K	Ca	Percentage composition from	to	response	Differential response
%P	Ch	0-300	400	0	0.31	0.40	0.09	
	Ch	300	0-400	0	0.48	0.40	-0.08	
%K	Hr	300	0-400	1000	1.00	1.60	0.60	
	Hk	300	0-400	1000	0.90	1.80	0.90	0.30
%Ca	Ch	0-300	400		2.05	2.40	0.35	
	Hk	0-300	400		1.80	2.10	0.30	
	Ch	300	0-400		2.45	2.40	-0.05	
	Hk	300	0-400		2.42	2.10	-0.30	0.27
%Mg	Ch	0	0-400	1000	1.05	0.53	-0.52	
	Hr	0	0-400	1000	1.03	0.62	-0.41	
	Ch	0	400	0-1000	0.60	0.53	-0.07	
	Hr	0	400	0-1000	0.58	0.62	0.04	0.11

to chemical composition of the leaves at the end of flowering for the variety Ch. The relationships between the percentage contents of P and K in the leaves and yield were weak in this experiment. There was question, however, if the multiple regression equations relating yield to leaf composition reflected true relationships.

Differential effects were strongest with respect to responses of the percentage K in the leaves to K application. These, nor any of the other differential effects observed, were associated with differential yield responses.

B. Field Experiment at the Carrington-Clyde Experimental Farm; Results and Discussion

1. Yield of soybeans as a function of fertilizer input variables

The analysis of variance for the yield of soybeans in Table 51 shows a significant effect of fertilizer treatments and highly significant differences between the four varieties. The F x V interaction effect was significant at the 0.25 level of probability.

The multiple regression of yield of soybeans on the fertilizer input variables was run for each variety and the partial regression coefficients tested using deviations from regression. The analysis of variance of the regressions shows that all varieties were affected by the fertilizer factor. The regression for the variety Hk reached only the 0.25 level of significance. The values of R^2 were very low however (Table 52). It appears from Table 53 that the yield responses observed for the varieties Bl, Hr and Hk were due to the linear and quadratic

Table 51. Analysis of variance for the yield of soybeans in the field experiment at the Carrington-Clyde Experimental Farm

Source	Degrees of freedom		Mean squares	F
Main plots	41			
Replications		1	1.0215	0.10
Fertilizer (F)		20	21.4323	2.16*
Error a		20	9.9202	
Sub-plots	126			
Varieties (V)		3	316.5283	71.00**
F x V		60	6.1602	1.38+
Error b		63	4.4581	

Table 52. Analyses of variance of the multiple regressions for the yield of soybeans of four varieties grown at the Carrington-Clyde Experimental Farm

Source	Degrees of freedom	Mean squares			
		Ch	Bl	Hr	Hk
Total	41	-	-	-	-
Regression	5	38.5738**	11.3869*	28.6618**	14.6140+
Deviations	36	3.8782	3.5168	6.4439	8.7265

components of the K effect. The K effect also reached significance for the variety Hk at the 0.05 level of probability. Tests for differential effects showed that yield differences between varieties when not fertilized reached the 0.01 level of significance, while differential fertilizer responses at the 0.10 and 0.25 level of significance were due to K and K^2 respectively (Table 54). The equation for the combined yield data may now be written

Table 53. Partial regression coefficients relating the yield of soybeans of four varieties grown at the Carrington-Clyde Experimental Farm to fertilization and their significance

Factor	Ch	Bl	Hr	Hk
b_o	33.7578**	32.3822**	39.5655**	32.1540**
P	0.6079+	0.2689	-0.0824	0.1299
K	-0.0546	1.1797**	0.9919	1.6200*
P^2	-0.0562	-0.0259	-0.0205	-0.0193
K^2	-0.0726+	-0.1562**	-0.2103**	-0.1919*
PK	-0.0402	0.0226	0.0667	-0.0092
R^2	0.5801	0.3102	0.3819	0.1887

Table 54. F-tests on differential yield responses of four varieties grown at the Carrington-Clyde Experimental Farm to fertilization

Factor	Mean squares	F
b_o	33.4127	7.49**
P	1.7231	< 1
K	10.3667	2.32++
P^2	0.5125	< 1
K^2	6.2960	1.41+
PK	2.2146	< 1

$$Y = b_{oCh}\,Ch + b_{oBl}\,Bl + b_{oHr}\,Hr + b_{oHk}\,Hk + b_1P + b_{2Ch}K\,Ch + b_{2Bl}K\,Bl + b_{2Hr}K\,Hr + b_{2Hk}K\,Hk + b_{4Ch}K^2\,Ch + b_{4Bl}K^2\,Bl + b_{4Hr}K^2\,Hr + b_{4Hk}K^2\,Hk.$$

Fitting this function resulted in the equation given in Table 55.

Table 55. Partial regression coefficients, b_i, of the combined yield equation for four varieties grown at the Carrington-Clyde Experimental Farm and their significance

Factor	b_i	$\underline{t}$
Ch	34.6815	42.52**
Bl	32.7037	40.10**
Hr	38.4186	47.10**
Hk	32.0845	39.23**
P	0.0272	0.28
K x Ch	-0.0986	0.24
K x Bl	1.3242	3.18**
K x Hr	1.3013	3.13**
K x Hk	1.6235	3.90**
K^2 x Ch	-0.0873	1.76++
K^2 x Bl	-0.1630	3.29**
K^2 x Hr	-0.2156	4.35**
K^2 x Hk	-0.1969	3.98**

Tests on the partial regression coefficients involving the varieties were made using error "b" from the analysis of variance of the combined yield data. The K^2 effect for Ch now reached the 0.10 level of significance. The K factor should not be eliminated from the yield equation for Ch.

Differences between varieties were tested by Duncan's multiple range test (Table 56). Hr differed from the other varieties at the 0.01 level, Ch and Hk differed at the 0.05 level of probability. Hr yielded highest when not fertilized in the experiment and Hk lowest. Ch differed significantly from the other varieties in its response to K. It is also the only variety which showed a negative response to K. None of the varieties differed with respect to K^2.

Table 56. Comparison of corresponding partial regression coefficients in the combined yield equation for four varieties grown at the Carrington-Clyde Experimental Farm

Nature of differential response	Variety and regression coefficients[a]			
Variety	Hk	Bl	Ch	Hr
	32.0845	32.7037	34.6815	38.4186
K	Ch	Hr	Bl	Hk
	-0.0986	1.3013	1.3242	1.6235
K^2	Hr	Hk	Bl	Ch
	-0.2156	-0.1969	-0.1630	-0.0873

[a]Comparisons failing to reach the 0.05 level of significance are underlined with a solid line. In addition those reaching the 0.05 level but not the 0.01 level of significance are underlined with a broken line.

Yield prediction equations for the individual varieties may now be written (Table 57). F-tests on the multiple regressions for the varieties Ch, Bl and Hr were significant at the 0.01 level and the variation accounted for by regression in the case of the variety Hk was larger than in the original regression and reached the 0.05 level of significance. The values of R^2 were low.

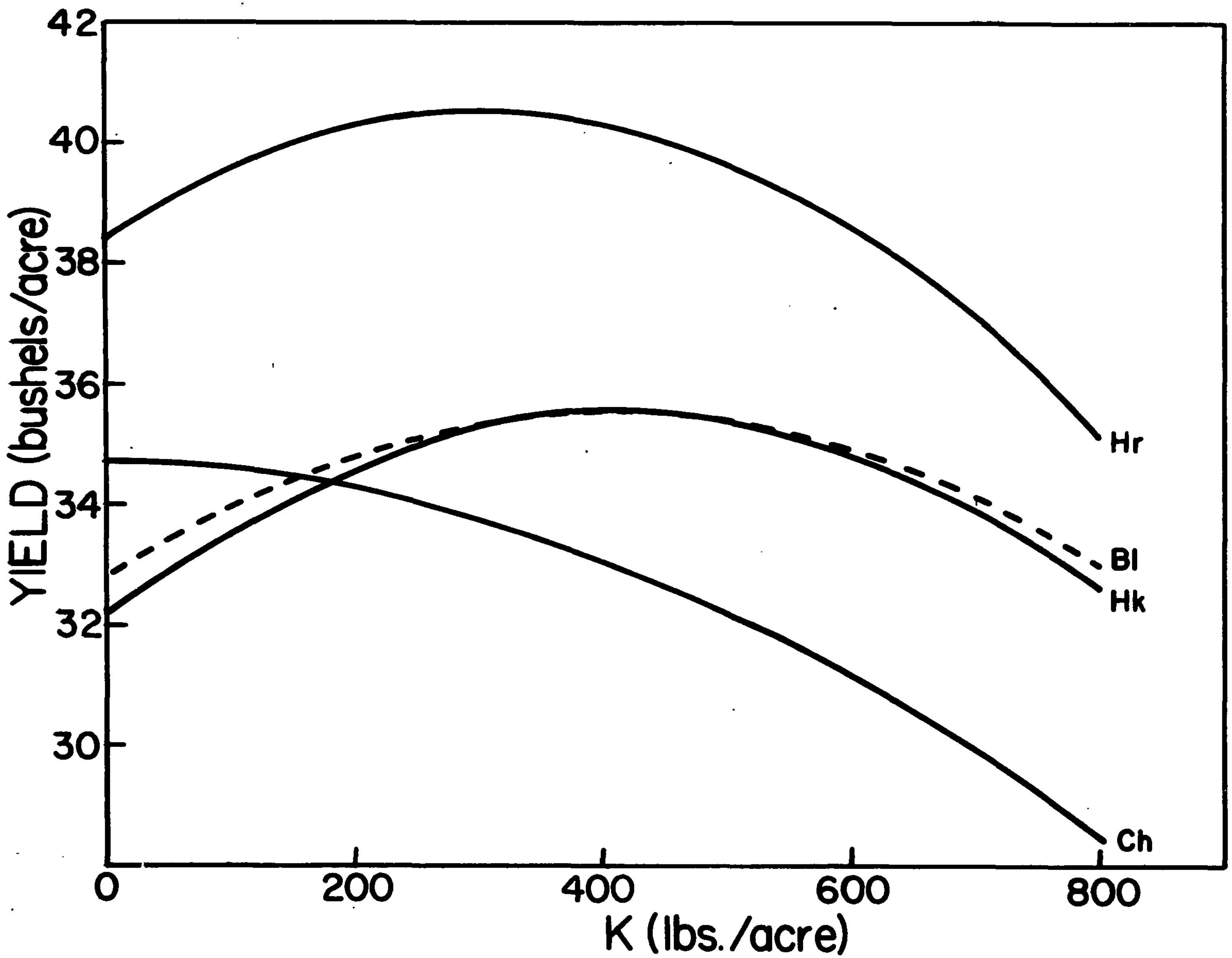
The fertilizer effects in the regression equations of Table 57 were tested using error "a" of the analysis of variance. The Ch variety lost all significance for the negative response to K under this test. Using these equations response curves to K were drawn. Figure 13 shows

Table 57. Partial regression coefficients of yield prediction equations for individual varieties at the Carrington-Clyde Experimental Farm, expressed in bushels per 100 lbs. of K applied per acre and their significance

Factor	Ch	Bl	Hr	Hk
b_o	34.7980**	32.8123**	38.5272**	32.1931**
K	-0.0985	1.3242	1.3013*	1.6235**
K^2	-0.0873	-0.1630*	-0.2156**	-0.1969**
R^2	0.5532	0.2643	0.3538	0.1876

an almost identical response to K for Bl and Hk. Hr outyielded all other varieties at any level of K fertilization. Ch yielded highest when no K was applied (calculated value -11 lbs. of K per acre using the original regression equation). The maximum yield for the varieties Bl, Hr and Hk occurred at respectively 406, 303 and 414 lbs. of K per acre. The magnitude of the predicted responses at this rate of K application is of the order of three bushels per acre. The range of application was sufficiently wide to include a portion of the region of negative responses in the curves due to excess KCl. When rates of 600 lbs. of K or higher were applied the growing plants were distinctly smaller four weeks after emergence and showed yellow discoloration of the leaves. Chippewa was often the most seriously affected. The other varieties yielded highest at an application of 300 to 400 lbs. of K per acre, but even here the leaves often had a paler green color than the check plots and sometimes

Figure 13. Yield response of four soybean varieties grown at the Carrington-Clyde Experimental Farm to K application; expressed in bushels per acre



YIELD (bushels/acre)
42
40
38
36
34
32
30
0
200
400
600
800
K (lbs./acre)
Hr
Bl
Hk
Ch

even showed slight yellowing. It is somewhat surprising that small but significant yield increases were obtained in response to K where the healthy appearance of the plant suffered from the fertilizer treatments. This, and also the fact that application of P, even when in combination with K, did not result in significantly higher yields on a soil testing low in P confirms earlier experiences that soybeans are generally less responsive to fertilizers than most other crops. This may be due to:

1. the inability of the plant to absorb a large amount of nutrients, or
2. its inability to utilize the additional nutrients absorbed for grain production.

It may be suspected that the roots of soybean plants in the field pass through the fertilized surface soil rather quickly and depend on nutrient absorption from deeper layers to a considerable extent. This trend would be accentuated by periods of dry weather. It would therefore be of interest to study nutrient accumulation by growing plants in pots under as nearly field conditions as possible. Such experiments have been laid out in a design including heavy rates of fertilization. The results will be discussed in later sections of this dissertation.

2. The effect of time of sampling on leaf composition

The purpose of sampling the soybean plants twice at short interval was to determine how critical the time of sampling is for measuring the effect of fertilization on leaf composition.

a. Percent P in the leaves The original data show a general downward trend in the P content of the leaves at the second sampling.

Table 58. Analysis of variance for the percent P in the leaves sampled twice about the end of flowering at the Carrington-Clyde Experimental Farm

Sources of variation	Degrees of freedom	Mean squares	F
Main plots			
Replications	1		1.71+
Treatments (T)	20		5.13**
Error a	20	0.0024	
Sub-plots			
Varieties (V)	3		55.26**
T x V	60		1.80*
Error b	63	0.0007	
Sub-sub-plots			
Stage (S)	1		115.09**
T x S	20		1.62
V x S	3		8.20**
T x V x S	60		1.29+
Error c	84	0.0004	

The analysis of variance for the percent P in Table 58 shows highly significant differences between dates of sampling (stage of development). The highly significant V x S interaction indicates that the effect of time of sampling was different from one variety to another. The T x S interaction reached the 0.10 level of significance, indicating that the treatment effect was not the same at the two stages of development.

The partial regression coefficients of the equations for the percent P in the leaves of four varieties sampled at two stages of development are shown in Table 59. The results of _t_-tests on corresponding regression coefficients between the 1st and 2nd sampling using error

Table 59. Partial regression coefficients relating the percent P in the leaves of four varieties grown at the Carrington-Clyde Experimental Farm to fertilization at two stages of development; and their significance

Sampling	Factor	Variety			
		Ch	Bl	Hr	Hk
First	b_o	0.36057**	0.34154**	0.36714**	0.37978**
	P	0.01221++	0.00905*	0.01765	0.00688
	K	-0.00134	-0.00015	-0.01252	-0.00630
	P^2	0.00137++	-0.00035	-0.00018	0.00002
	K^2	0.00055	-0.00007	0.00134	0.00044
	PK	-0.00228**	-0.00005	-0.00145+	-0.00033
Second	b_o	0.33939	0.30163**	0.33305**	0.34916**
	P	0.01260++	0.01511**	0.01212+	0.01092*
	K	-0.00675	-0.00564+	0.00968+	-0.00134
	P^2	0.00072	-0.00098*	-0.00035	-0.00039
	K^2	0.00105+	0.00045	-0.00101	-0.00026
	PK	-0.00109+	-0.00011	-0.00061	-0.00031

Table 60. Values of _t_ for differential responses in the percent P in the leaves of four varieties grown at the Carrington-Clyde Experimental Farm, between two stages of development and significant at the 0.20 or higher level of probability

Factor	Ch	Bl	Hr	Hk
b_o	-	2.34*	2.00*	1.80++
P	-	-	-	-
K	-	-	3.44**	-
P^2	-	-	-	-
K^2	-	-	3.32**	-
PK	1.90++	-	-	-

"c" from the analysis of variance are shown in Table 60.

The values of _t_ in the first line further specify the V x S interaction effect of the analysis of variance as being due largely to the Bl and Hr varieties. The variety Hr particularly showed that the linear and quadratic effects of K on the percent P changed over the nine day period with significance at the 0.01 level of probability.

b. _Percent K in the leaves_ The analysis of variance in Table 61 shows highly significant effects due to stage of sampling and its interactions with varieties and fertilizer treatments.

The partial regression coefficients of the equations for the percent K in the leaves of four varieties for dates of sampling (Table 62) and the _t_-tests on corresponding coefficients between stages (Table 63) show that the variety effect of Bl on the percent K was highly significantly reduced at the later date of sampling which specifies the corresponding interaction in the analysis of variance. The linear and quadratic effects of K application were responsible for the T x S interaction effect and this occurred at variable levels of significance for each of the varieties.

The change in variety effect, together with that in treatment effect determine whether the percentage composition will increase or decrease with time. Where significant to any degree the change in the variety effect with time is consistently downward. This indicates that the nutrient content of the leaves is decreasing with time when no fertilizer is applied. Where this holds for any nutrient in the varieties Hr and Hk it means that the movement out of the leaves started at or before the end of flowering, because Hr and Hk had not quite reached this stage at the first sampling.

Table 61. Analysis of variance for the percent K in the leaves, sampled twice about the end of flowering at the Carrington-Clyde Experimental Farm

Sources of variation	Degrees of freedom	Mean squares	F
Main plots			
Replications	1		1.08
Treatments (T)	20		12.76**
Error a	20	0.0356	-
Sub-plots			
Varieties (V)	3		46.30**
T x V	60		< 1
Error b	63	0.0190	-
Sub-sub-plots			
Stage (S)	1		28.25**
T x S	20		2.99**
V x S	3		13.38**
T x V x S	60		1.36+
Error c	84	0.0127	-

Contours for the percent K were computed from the equations for the first and second sampling of the variety B1 and plotted in Figure 14 at an interval of 0.05 %K. The broken lines represent a projection of the lines of intersection between the two surfaces on the horizontal plane. The area between the broken lines indicates the area of P and K combinations resulting in a higher surface of percent K for the later sampling. It would generally be expected that the percent K in the leaves decreases after completion of flowering due to translocation of nutrients to the growing soybeans. This is borne out by the contours in Figure 14. The surface for the percent K at the later stage is generally situated below that for the earlier sampling. This trend can be reversed by applying K

Table 62. Partial regression coefficients relating the percent K in the leaves of four varieties grown at the Carrington-Clyde Experimental Farm, to fertilization, at two stages of development; and their significance

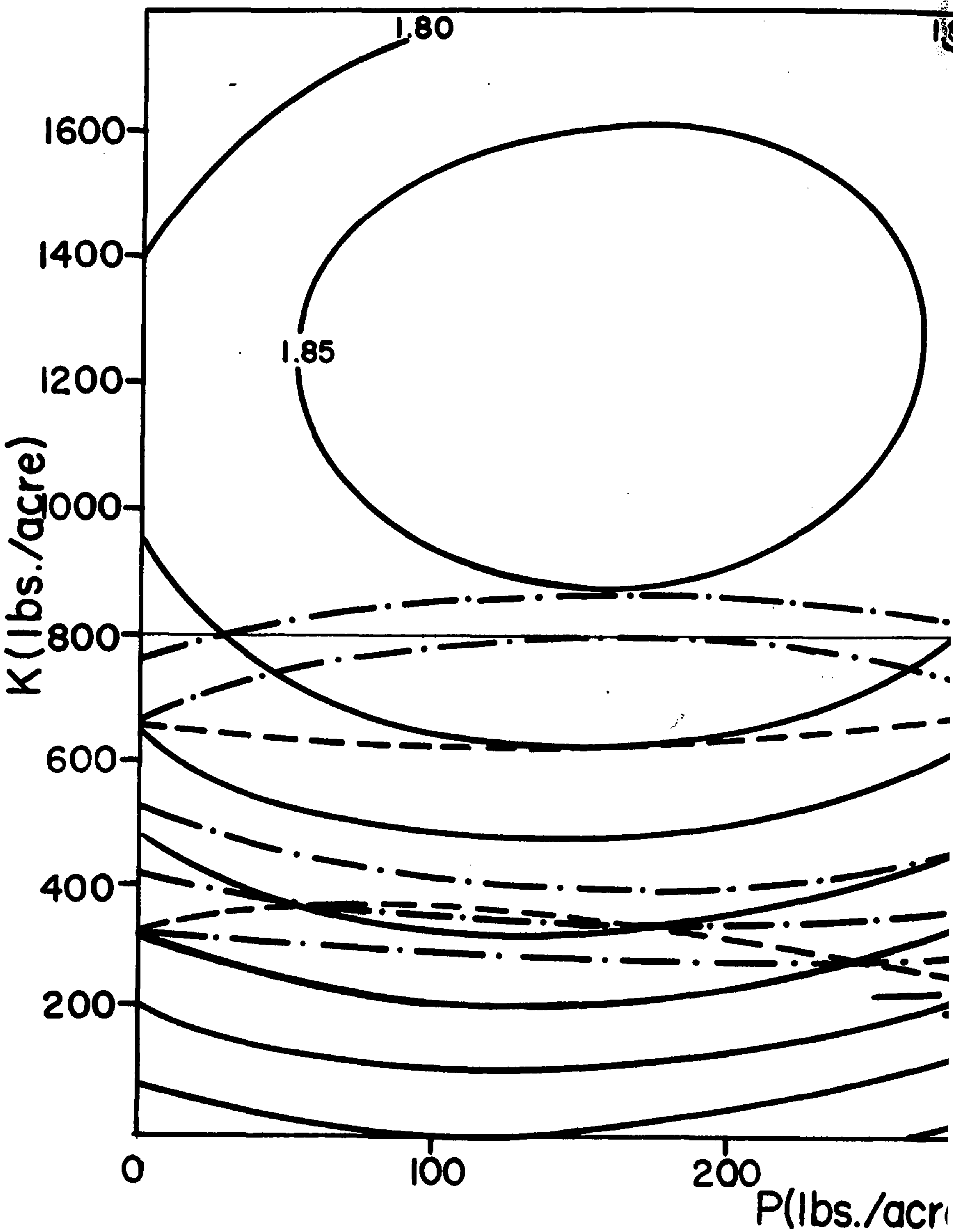
Sampling	Factor	Variety			
		Ch	Bl	Hr	Hk
First	b_o	1.3521**	1.5091**	1.2943**	1.4343**
	P	0.0164	0.0326	-0.0187	-0.0512
	K	0.1135**	0.0514	0.0954**	0.1334**
	P^2	-0.0031	-0.0065	0.0004	0.0029
	K^2	-0.0107**	-0.0022	-0.0089**	-0.0117**
	PK	0.0009	0.0008	0.0000	0.0062*
Second	b_o	1.2440**	1.2183**	1.2257**	1.4469**
	P	0.0131	0.0306	-0.0081	-0.0371
	K	0.1631**	0.1826**	0.1629**	0.2222**
	P^2	-0.0015	-0.0040	0.0005	0.0005
	K^2	-0.0133**	-0.0155**	-0.0139**	-0.0226**
	PK	-0.0010	-0.0008	0.0009	0.0064*

Table 63. Values of _t_ for differential responses in the percent K in the leaves of four varieties grown at the Carrington-Clyde Experimental Farm, between two stages of development and significant at the 0.20 or higher level of probability

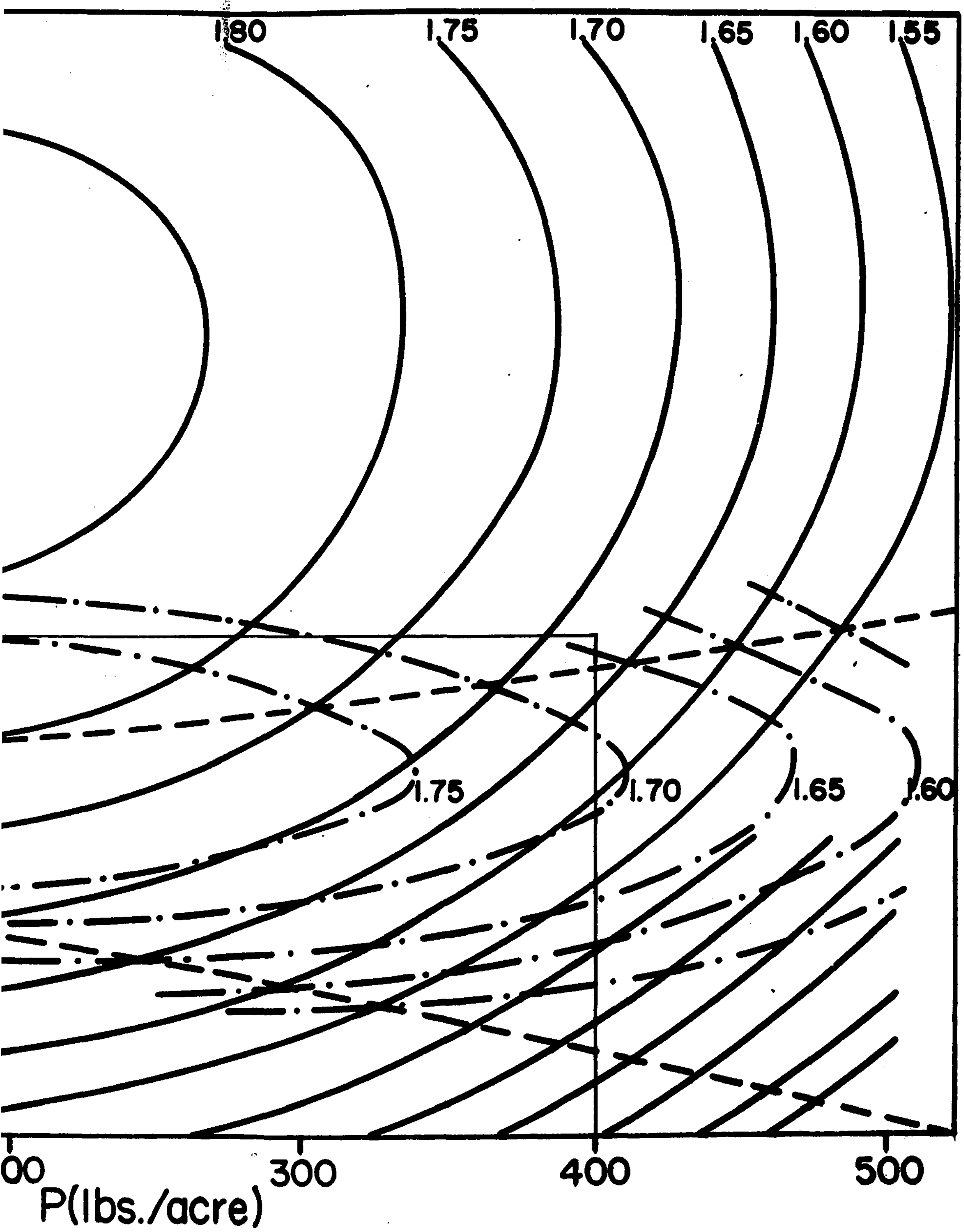
Factor	Ch	Bl	Hr	Hk
b_o	-	3.12**	-	-
P	-	-	-	-
K	1.41+	3.72**	1.92++	2.52*
P^2	-	-	-	-
K^2	-	3.45**	1.30+	2.81**
PK	-	-	-	-

Figure 14. Contours for the percent K in the leaves of the variety Blackhawk sampled at the end of flowering and nine days thereafter at the Carrington-Clyde Experimental Farm with applied P and K as variables; and the projection of the lines of intersection between the 2 surfaces

Sampling at the end of flowering
Later sampling
Projected lines of intersection
Limits of investigated area



1.80
1.85
1600
1400
1200
1000
800
600
400
200
K(lbs./acre)
0
100
200
P(lbs./acr



1.80
1.75
1.70
1.65
1.60
1.55
1.75
1.70
1.65
1.60
00
300
400
500
P(lbs./acre)

fertilizer between the levels of 300 and 700 lbs. of K per acre. This means that certain high rates of K application can maintain the percent K in the leaves at a high level longer than is the case with K applications up to 300 lbs. per acre. It would be interesting to determine how long after the beginning of soybean formation this trend can be maintained.

This phenomenon is largely independent of P application as can be seen from the position of the projected lines of intersection between the two surfaces. It should be emphasized that this effect occurs at very high levels of K application. The fact that maxima occur at a certain level of K application, while the percent K drops with further increase in K application may have little meaning. It is presumably due to the type of function (quadratic) fitted to the data. The fact that the maxima occur at a level of 150 lbs. of P per acre is presumably a correct estimation of actual plant behavior.

c. Percent N in the leaves   The effect of stage of sampling and its interaction with varieties in the analysis of variance shown in Table 64 were highly significant, while the T x S interaction was significant only at the 0.25 probability level.

The partial regression coefficients of the equations for the percent N in the leaves of four varieties sampled at two stages of development are given in Table 65. The corresponding regression coefficients at the first and second sampling were tested for differences. Values of *t* reaching significance at the 0.20 or higher level of probability are shown in Table 66.

It appears from Table 66 that there were no differences due to

Table 64. Analysis of variance for the percent N in the leaves sampled twice at about the end of flowering at the Carrington-Clyde Experimental Farm

Sources of variation	Degrees of freedom	Mean squares	F
Main plots			
Replications	1		12.00**
Treatments (T)	20		2.97**
Error a	20	0.0601	-
Sub-plots			
Variety (V)	3		4.32**
T x V	60		1.03
Error b	63	0.0750	-
Sub-sub-plots			
Stage (S)	1		75.61**
T x S	20		1.39+
V x S	3		15.77**
T x V x S	60		< 1
Error c	84	0.0696	-

varieties other than that for Ch at the 0.20 level of significance. Just as in case of the percent P and percent K in the leaves, the K fertilizer treatments again influenced the effect due to time of sampling. The linear and quadratic effects of K reached the 0.05 and 0.10 levels of probability in this respect for the varieties Bl and Hr. Some of the equations from Table 65 were used to study the factors affecting the percent N in the leaves further. The variety Hr was taken as an example. Contours for the percent N were computed and plotted at intervals of 0.05%N. The area between the broken lines indicates the area of P and K combinations resulting in a lower percent N at the later sampling date (Figure 15). It would be expected that the percent N in the leaves would

Table 65. Partial regression coefficients relating the percent N in the leaves of four varieties grown at the Carrington-Clyde Experimental Farm to fertilization at two stages of development and their significance

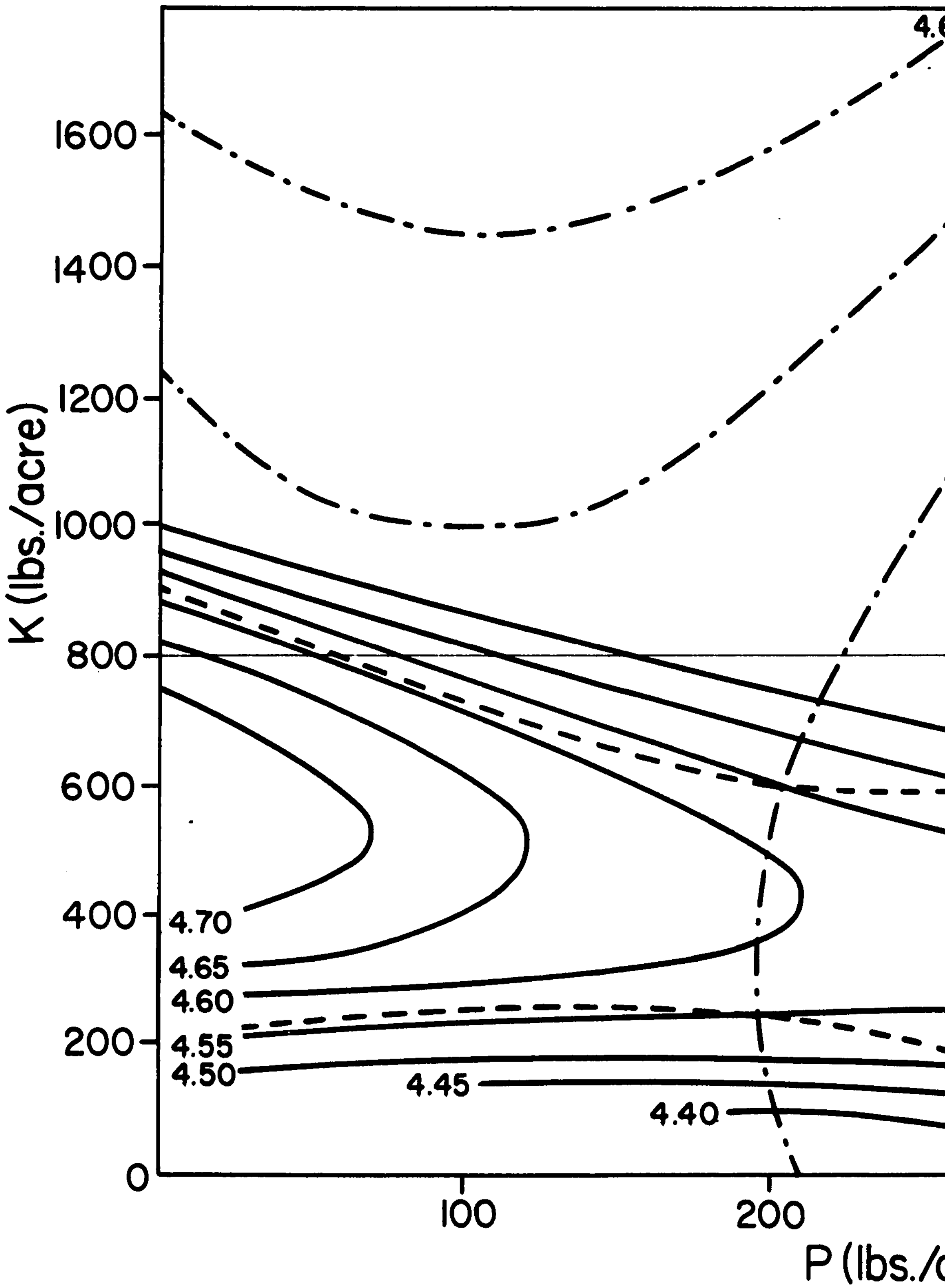
Sampling	Factor	Variety			
		Ch	Bl	Hr	Hk
First	b_o	4.4188**	4.4855**	4.2348**	4.4143**
	P	0.0198	-0.0453	0.0114	-0.1070*
	K	0.5571	0.1305*	0.1860*	0.1301*
	P^2	0.0030	0.0030	0.0018	0.0089+
	K^2	-0.0007	-0.0144*	-0.0164++	-0.0156*
	PK	-0.0102+	0.0029	-0.0117+	0.0035
Second	b_o	4.1374**	4.2297**	4.5772**	4.4087**
	P	0.0292	0.0264	0.0170	-0.0297
	K	-0.0278	-0.0364	-0.0062	0.0584
	P^2	-0.0040	-0.0078+	-0.0057	0.0024
	K^2	0.0079+	0.0029	0.0007	-0.0085+
	PK	-0.0020	0.0059	0.0005	-0.0018

Table 66. Values of t for differential responses in the percent N of four varieties grown at the Carrington-Clyde Experimental Farm, between two stages of development and significant at 0.20 or higher level of probability

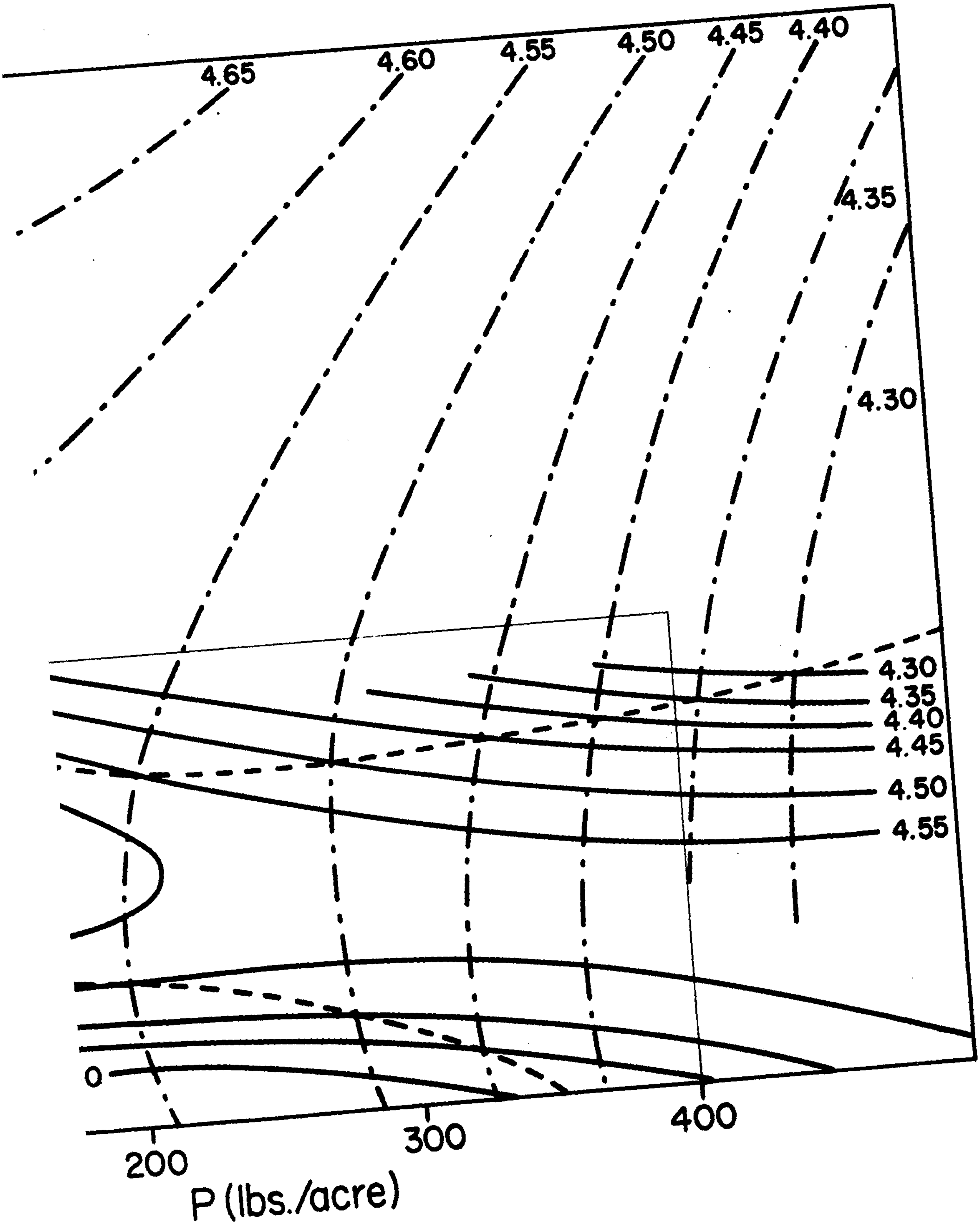
Factor	Ch	Bl	Hr	Hk
b_o	1.29+	-	-	-
P	-	-	-	-
K	-	2.03*	2.33*	-
P^2	-	-	-	-
K^2	-	1.91++	1.88++	-
PK	-	-	1.41+	-

Figure 15. Contours for the percent N in the leaves of the variety Harosoy sampled 9 days before the end of flowering and at the end of flowering at the Carrington-Clyde Experimental Farm with applied P and K as variables; and the projection of the lines of intersection between the two surfaces

First sampling
Sampling at the end of flowering
Projected lines of intersection
Limits of investigated area



4.6
1600
1400
1200
1000
800
600
400
200
0
K (lbs./acre)
4.70
4.65
4.60
4.55
4.50
4.45
4.40
100
200
P (lbs./a


4.65
4.60
4.55
4.50
4.45
4.40
4.35
4.30
4.30
4.35
4.40
4.45
4.50
4.55
0
200
300
400
P (lbs./acre)

be highest at the later sampling since this represents the end of flowering for this variety. This holds true outside the broken lines. It appears from Figure 15 that this effect is reversed by a K application in the range of 200 to 700 lbs. of K per acre approximately.

The highest N content (4.70%) at the first sampling is predicted when no P is applied and at 500 to 600 lbs. of K per acre. This level cannot be reached at the later date irrespective of P and K application.

3. Chemical composition of the leaves as a function of fertilizer input variables

a. Percent P in the leaves   Since some highly significant differences in variety and treatment effects were incurred during a 9-day period at about the end of flowering it is important to sample the growing plant as close to the intended stage of development as possible.

The comparison of the chemical composition of the four varieties will therefore be made on the data for the first sampling for Ch and Bl and those for the second sampling for the varieties Hr and Hk.

Table 67 shows that the percent P in soybean leaves was not closely related to the P and K supplied to the soil. F-tests on the overall regressions were significant at the 0.01 level for the varieties Ch, Bl and Hk and at the 0.05 level of probability for the variety Hr, but the values of R^2 were low. Only in the case of Hawkeye did the linear effect of P have a significant effect on the percent P in the leaves at the 0.05 level.

The differences between the varieties were tested by Williams' technique, using error "b" from the analysis of variance for the percent P

Table 67. Partial regression coefficients relating the percent P in the leaves of four varieties grown at the Carrington-Clyde Experimental Farm, at the end of flowering to fertilization and their significance

Factor	Ch	Bl	Hr	Hk
b_o	0.36057**	0.34154**	0.33305**	0.34916**
P	0.01221++	0.00905*	0.01212+	0.01092*
K	-0.00134	-0.00015	0.00968+	-0.00134
P^2	0.00137++	-0.00035	-0.00035	-0.00039
K^2	0.00055	-0.00007	-0.00101	-0.00026
PK	-0.00228	-0.00005	-0.00061	-0.00031
R^2	0.6912	0.5327	0.2910	0.4884

Table 68. F-tests on differential responses in the percent P in the leaves among four varieties grown at the Carrington-Clyde Experimental Farm

Factor	Mean squares	F
b_o	0.00044	< 1
P	-	< 1
K	0.00058	< 1
P^2	0.00127	1.76+
K^2	0.00071	< 1
PK	0.00220	3.04*

There were significant differences among the varieties with respect to the PK interaction at the 0.05 level at a lower level of probability with regard to P^2 (Table 68). It is evident from the partial regression coefficients that Ch was the nonconforming variety in this respect.

Using this information the data for the four varieties were combined into the equation shown in Table 69. Tests on the coefficients involving varieties were made using error "b" from the analysis of variance (Table 58). The fertilizer effects were tested using error "a".

This combined analysis largely confirms the results of the individual regressions. A difference is that the PK interaction for the variety Ch reached significance at the 0.05 level whereas it did not before.

Differences involving varieties were compared by Duncan's multiple range test and it was found that the variety Ch differed from Bl and Hk at the 0.01 level of significance (Table 70). Ch was also different at the 0.01 level of probability from all other varieties with respect to the quadratic effect of P.

A differential response to the PK interaction existed (Table 68) for Ch versus Bl and Hr at the 0.01 level and versus Hk at 0.05 level of significance. In conclusion it may be said that the percent P in the leaves at the end of flowering under the conditions of the experiment was influenced by the linear effect of P, while for Ch the quadratic effect of P and the PK interaction also were significant. Ch differed from other varieties with respect to these effects in the sense that it had a higher percent P which was further elevated by the P^2 effect and was decreased more by the PK interaction than was the case for the other varieties.

Using the original equations the percent P can be plotted as a function of P fertilizer applied and setting K at 0 since K did not

Table 69. Partial regression coefficients, b_i, of the combined equation for the percent P in the leaves of four varieties grown at the Carrington-Clyde Experimental Farm and their significance

Factor	b_i	t
Ch	0.3637	37.98**
Bl	0.3349	34.97**
Hr	0.3470	36.24**
Hk	0.3387	35.37**
P	0.0111	2.04*
K	0.0017	< 1
Ch x P^2	0.0013	1.85+
Bl x P^2	-0.0005	< 1
Hr x P^2	-0.0005	< 1
Hk x P^2	-0.0002	< 1
K^2	-0.0002	< 1
Ch x PK	-0.0018	2.48*
Bl x PK	-0.0002	< 1
Hr x PK	-0.0004	< 1
HK x PK	-0.0009	1.17
R^2	0.6150	

materially affect the percent P (Figure 16). The dissimilar behavior of Ch is interesting in view of Howell and Bernard's (1962) finding that Ch belongs to the group of soybean varieties which is very sensitive to high P concentrations in nutrient culture. It appears that its P content reached higher values than that of other varieties under identical fertilization in the field. Also this relationship becomes clearly curvilinear at high P rates within the investigated range. It would be interesting to know whether this is a percentage increase only or an increase in total amount of P absorbed. It is also interesting that

Table 70. Comparison of corresponding partial regression coefficients in the combined equation for the percent P in the leaves of four varieties grown at the Carrington-Clyde Experimental Farm, using Duncan's multiple range test

Nature of differential response	Variety, regression coefficients and significance of differences[a]			
Variety	Bl 0.33490	Hk 0.33866	Hr 0.34702	Ch 0.36374
P	Bl -0.00050	Hr -0.00037	Hk -0.00016	Ch 0.00131
PK	Ch -0.00182	Hk -0.00086	Hr -0.00035	Bl -0.00021

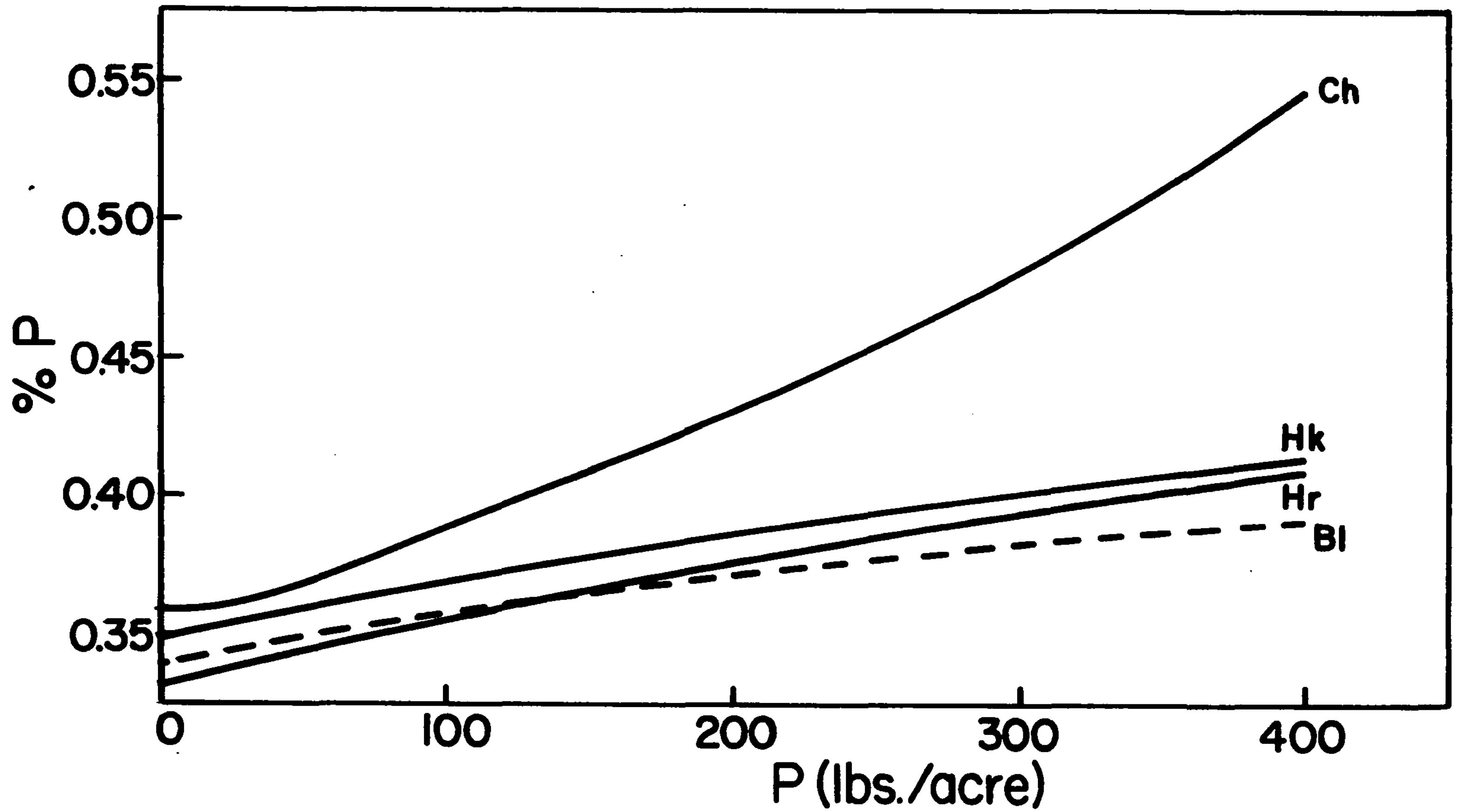
[a]Comparisons failing to reach the 0.05 level of significance are underlined with a solid line. In addition those reaching the 0.05 level but not the 0.01 level of significance are underlined with a broken line.

the difference is noticeable from the lowest rate of P application in this field study, whereas Fletcher and Kurtz (1964) observed a difference in percent P between the P-intolerant variety Lincoln and the P-tolerant variety Chief only at rates of application exceeding 2000 lbs. of P per acre in a greenhouse study.

b. <u>Percent K in the leaves</u> The multiple regression equations for the percent K as a function of P and K fertilizers applied are given in Table 71.

The percent K is very closely related to the linear and quadratic

Figure 16. Response of percent P in the leaves at the end of flowering as a function of P application at 0 lbs. of K for four varieties grown at the Carrington-Clyde Experimental Farm



0.55
0.50
0.45
0.40
0.35
% P
0
100
200
300
400
P (lbs./acre)
Ch
Hk
Hr
Bl

Table 71. Partial regression coefficients relating the percent K in the leaves of four varieties grown at the Carrington-Clyde Experimental Farm, at the end of flowering to fertilization and their significance

Factor	Ch	Bl	Hr	Hk
b_o	1.35211**	1.50913**	1.22568**	1.44693**
P	0.01639	0.03260	-0.00812	-0.03711
K	0.11354**	0.05142	0.16288**	0.22217**
P^2	-0.00308	-0.00645	0.00047	0.00049
K^2	-0.01073**	-0.00218	-0.01391**	-0.02256**
PK	0.00087	0.00076	0.00087	0.00636*
R^2	0.4466	0.2096	0.6994	0.7430

Table 72. F-tests on differential responses in the percent K in the leaves among four varieties grown at the Carrington-Clyde Experimental Farm

Factor	Mean squares	F
b_o	0.04467	2.35++
P	0.01895	< 1
K	0.10805	5.69**
P^2	0.01879	< 1
K^2	0.12045	6.34**
PK	0.01668	< 1

effects of K fertilization, but in the case of Bl it was not related. The regression for the percent K in the leaves of the variety Bl was not significant at the 0.05 level of probability and the value of R^2 for the equation was low. F-tests on the overall regression for the other varieties were significant at the 0.01 level. The PK interaction affected the percent K of the leaves of Hk. Williams' test on corresponding coefficients showed highly significant differences in response among the varieties with respect to the linear and quadratic effect of K. Without fertilization the percent K was different for each variety at the 0.10 level of significance (Table 72).

The data for the four varieties were combined according to the above findings into one equation as shown in Table 73. Tests on the coefficients involving varieties were made using error "b" of the analysis of variance (Table 61). The fertilizer effects were tested using error "a". The analysis, combined for the four varieties, confirms the results from the individual regressions. The significant PK interaction for Hk does not show in the pooled coefficient for PK, however.

Varietal differences and differential responses to K between varieties were tested by Duncan's multiple range procedure. The results of Table 74 show that there were highly significant varietal differences in percent K between Bl and Hr, while Bl differed from Hk at the 0.05 level of significance. A differential response to the linear component of K distinguished Hk from Bl and Ch at the 0.01 level, while Hk and Hr, and Hr and Bl differed at the 0.05 level of probability. Bl and Hk differed at the 0.01 level with respect to the quadratic K effect, while Bl and Hr, and Ch and Hk differed at the 0.05 level of probability.

Using the original equations the change in percent K with increasing K application and without applied P were calculated. The variety Hk had a higher K content in the leaves over most of the range of K applied

Table 73. Partial regression coefficients, b_i, of the combined equation for the percent K in the leaves of four varieties grown at the Carrington-Clyde Experimental Farm and their significance

Factor	b_i	t
Ch	1.3906	23.39**
Bl	1.5287	25.71**
Hr	1.2545	21.10**
Hk	1.3602	22.88**
P	0.0010	0.05
P^2	-0.0021	0.94
PK	0.0022	1.10
Ch x K	0.1101	3.93**
Bl x K	0.0545	1.94
Hr x K	0.1520	5.42**
Hk x K	0.2332	8.32**
Ch x K^2	-0.0110	3.37**
Bl x K^2	-0.0033	1.01
Hr x K^2	-0.0132	4.06**
Hl x K^2	-0.0219	6.71**
R^2	0.5860	

than the other varieties. Figure 17 illustrates the differences between the varieties, some of which were significant as discussed. Those varieties which show a maximum in percent K do so at a level of 500 to 600 lbs. of K per acre.

c. Percent N in the leaves The multiple regression equation for the percent N in the leaves at the end of flowering as a function of P and K fertilization for each variety is shown in Table 75. It appears from Table 75 that the percent N in the leaves for Bl was related to K application while the percent K was shown to be insensitive to this. Generally the percent N was not influenced by P and K nutrients applied.

Table 74. Comparison of corresponding partial regression coefficients in the combined equation for the percent K in the leaves of four varieties grown at the Carrington-Clyde Experimental Farm using Duncan's multiple range test

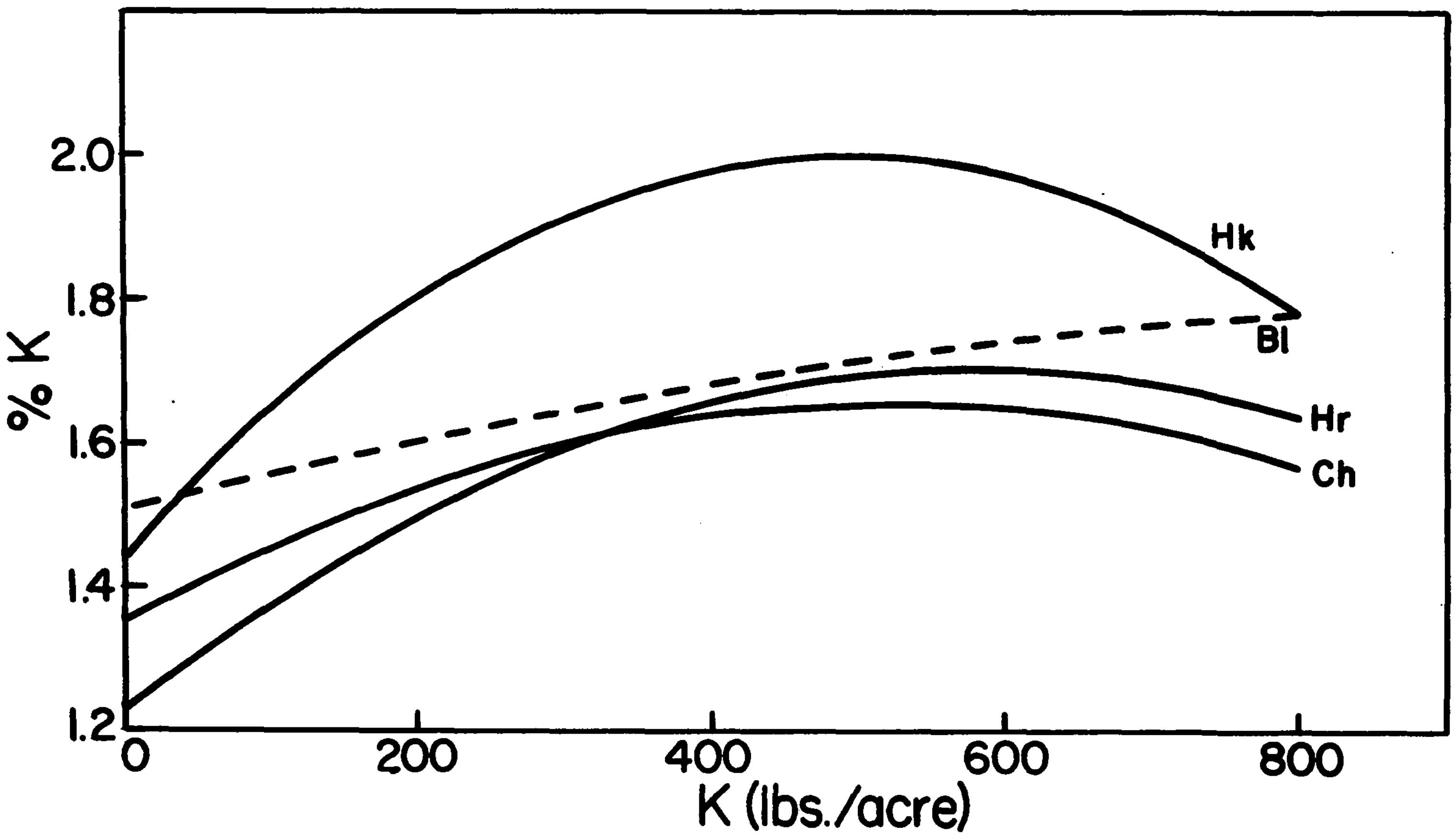
Nature of differential responses	Variety, regression coefficients and significance of differences[a]			
Variety	Hr	Hk	Ch	Bl
	1.2545	1.3602	1.3906	1.5287
K	Bl	Ch	Hr	Hk
	0.0545	0.1101	0.1520	0.2332
K^2	Hk	Hr	Ch	Bl
	-0.0219	-0.0132	-0.0110	-0.0033

[a]Comparisons failing to reach the 0.05 level of significance are underlined with a solid line. In addition those reaching the 0.05 level but not the 0.01 level of significance are underlined with a broken line.

Table 75. Partial regression coefficients relating the percent N in the leaves of four varieties grown at the Carrington-Clyde Experimental Farm at the end of flowering to fertilization and their significance

Factor	Ch	Bl	Hr	Hk
b_o	4.4188**	4.4855**	4.5772**	4.4087**
P	0.0198	-0.0453	0.0170	-0.0297
K	0.0571	0.1305*	-0.0062	0.0584
P^2	0.0030	0.0030	-0.0057	0.0024
K^2	-0.0007	-0.0144*	0.0007	-0.0095+
PK	-0.0102+	0.0029	0.0005	-0.0018
R^2	0.0550	0.2077	0.1254	0.1172

Figure 17. Response of percent K in the leaves at the end of flowering as a function of K application at 0 lbs. of P for four varieties grown at the Carrington-Clyde Experimental Farm

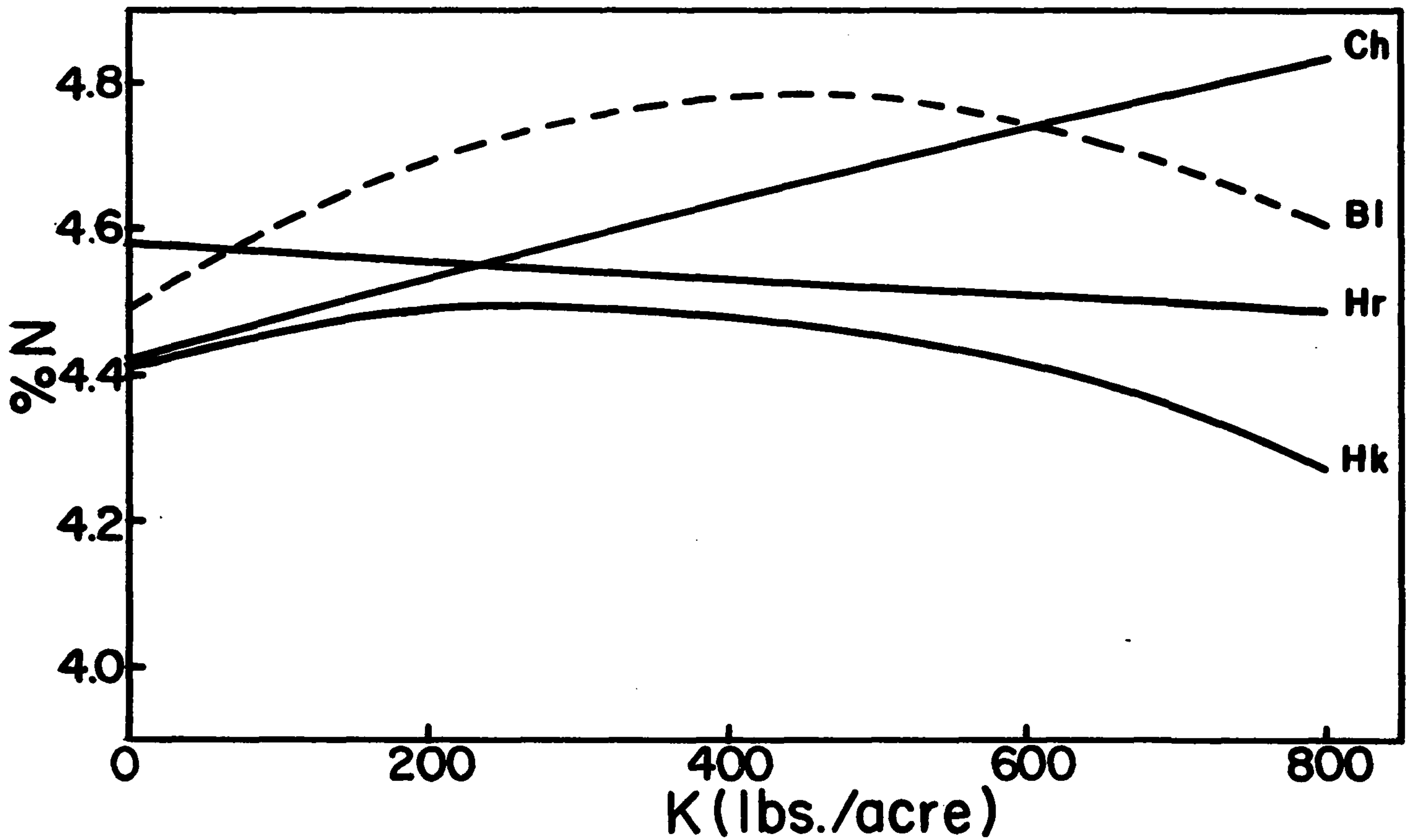

2.0
1.8
1.6
1.4
1.2
% K
0
200
400
600
800
K (lbs./acre)
Hk
Bl
Hr
Ch

The values of R^2 were very low and none of the four regressions could explain a sufficient amount of variation for the F-test in the overall regression to reach significance at the 0.05 level of probability. The differences between the varieties themselves or their differential responses to fertilizer failed to reach significance even at the 0.25 level using Williams' test. All data were therefore combined in the equation given in Table 76. The analysis confirms the earlier conclusion that only K affected the percent N in the leaves. Using the original equations the dependence of the percent N on K application and without P can be represented graphically as shown in Figure 18. The graphs illustrate the diverging trends in the response of percent N to K fertilization. It must be remembered that the only significant relationship may be that of the influence of K application on the percent N in the leaves of the variety B1. B1 reached a maximum percent N at approximately 450 lbs. of K per acre.

Table 76. Partial regression coefficients, b_i, of the combined equation for the percent N in the leaves of four varieties grown at the Carrington-Clyde Experimental Farm and their significance

Factor	b_i	*t*
b_o	4.4725	111.12**
P	-0.0096	< 1
K	0.0599	2.88**
P^2	0.0007	< 1
K^2	-0.0600	2.62*
PK	-0.0022	1.08
R^2	0.0309	

Figure 18. Response of percent N in the leaves at the end of flowering as a function of K application at 0 lbs. of P for four varieties grown at the Carrington-Clyde Experimental Farm


%N
4.8
4.6
4.4
4.2
4.0
0
200
400
600
800
K(lbs./acre)
Ch
Bl
Hr
Hk

4. Conclusions

Highly significant yield responses to K application and a lack of response to P despite the low P status of the site observed at the Carrington-Clyde Experimental Farm were similar to the results at the Howard County Experimental Farm. The magnitude of the K response was smaller than in Howard County. The maximum predicted K response was of the order of three bushels per acre at very high rates of K fertilization. The variety Ch differed considerably from the other varieties in its response to K and this divergence caused differential responses to K among the varieties to test significant at the 0.10 level of probability. In the Howard County Experiment a similarly weak indication of a differential effect occurred with respect to P^2. The variety Hr yielded higher than the other varieties over the entire range of fertilization which agreed with the conclusion reached from the Howard County experiment.

It was found that the P, K and N content of soybean leaves changed significantly over a 9-day period at the end of flowering. A highly significant difference existed in the effect of K application on the percent P in the leaves of the variety Hr. The percent K in the leaves of several varieties was influenced differentially by K application at the two stages of development at the 0.01 level of significance. It was shown for the variety Bl that by applying certain high rates of K the general downward trend of the K content in the leaves over the 9-day period may be reversed. K application also affected and reversed the trend in the percent N in the leaves with time of sampling.

The percent P was affected by P application at the 0.05 level of significance and Ch differed from the other varieties in P content of the leaves and its response to the P^2 and the PK interaction effects at the 0.01 level of probability which would reflect the high P-sensitivity of this variety.

Ch had also the highest P content in the Howard County experiment over a similar range of P application. The P content of Hr was nearly as high as that of Ch there and the differences were not significant.

The percent K in the leaves was highly significantly affected and the varieties differentially affected by the K and K^2 effects as was the case in the Howard County experiment. In both experiments the variety Hk had the highest K content in the leaves over most of the range of fertilization. The variation in percent N in the leaves could not be explained satisfactorily by the factors of fertilization.

IV. POT EXPERIMENTS WITH SOYBEAN LINES INTRODUCED FROM FAR-EASTERN COUNTRIES

A. Pot Experiment 1962; Results and Discussion

1. Leaf symptoms in relation to chemical composition of the leaves

The wide range of fertilizer application employed resulted in visible differences in the apparent health and growth of the plants at a very young stage of development. Responses to P were exceptionally strong and included optimum growing conditions as well as damage due to rates of application in the area of P excess. The responses were of an unusual nature. Plants receiving high rates of P grew taller and had thicker stems and larger leaves than any treatments consisting of K and/or Ca application, but also showed distinct interveinal leaf discoloration. Other symptoms of abnormality were brown necrotic specks on the surface and periphery of the cotyledons (Plates 6 and 7). Later, the cotyledons and unifoliate leaves were dropped, the trifoliate leaves turned yellow-brown, and assumed a cup-shaped form (Plate 8). They tended to point in upward direction and felt harder to the touch than normal leaves. Symptom development among treatments receiving P at the rate of 800 pp2m was most severe where P was applied alone (treatment 4-0-0 in Table 77). They were followed by the pots also containing high K (4-4-0), then (4-0-4), while the (4-4-4) treatments were only very slightly affected (Plates 9 and 10).

The cause of these unusual responses was no doubt related to:

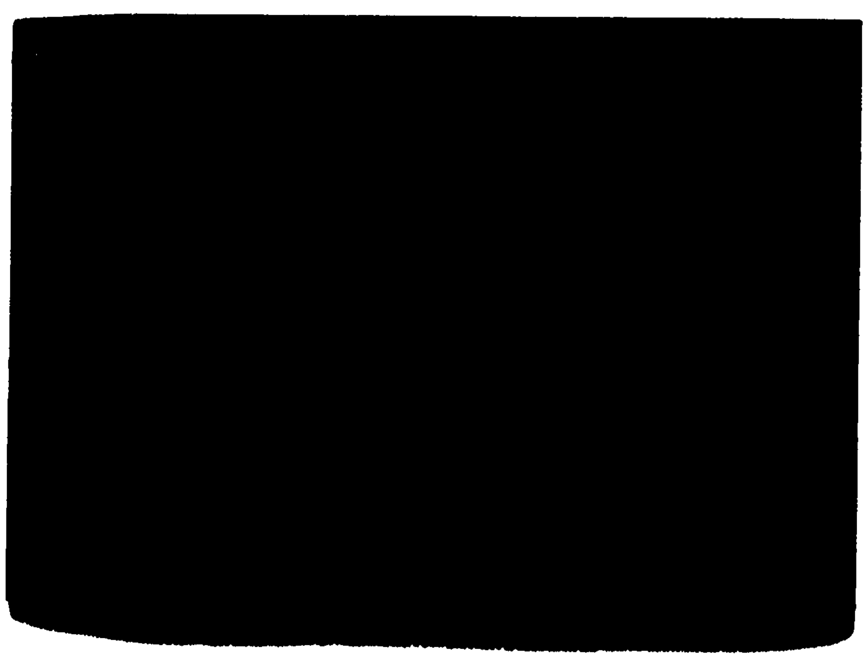
Table 77. Leaf-symptom development in relation to actual P and K content of the leaves and number of nodules per three plants at the stage of 4.5 trifoliate leaves for two soybean lines grown in pots in 1962

Rate of fertilization			Degree of symptom development[a]	Average % composition of the leaves				Number of nodules	
				%P		%K			
P	K	Ca		Entry 4	Entry 5	Entry 4	Entry 5	Entry 4	Entry 5
0	0	4	0	0.15	0.16	0.95	1.22	16	39
0	4	0	0	0.15	0.15	1.88	1.79	135	75
0	4	4	0	0.12	0.12	1.82	1.93	18	17
4	0	0	5	3.85	3.15	1.45	1.36	65	90
4	0	4	3	2.95	2.65	1.23	1.35	167	81
4	4	0	4	2.68	2.18	3.63	3.15	389	319
4	4	4	1	1.74	1.22	2.80	2.67	449	190
0	0	0	0	0.21	0.21	1.56	1.35	48	19

[a]Relative scale for the experiment.

Plate 6. Pot experiment 1962; from left to right: control and pots receiving high rates of Ca, K, K+Ca and P respectively

Plate 7. Pot experiment 1962; close-up of check and high P treatments



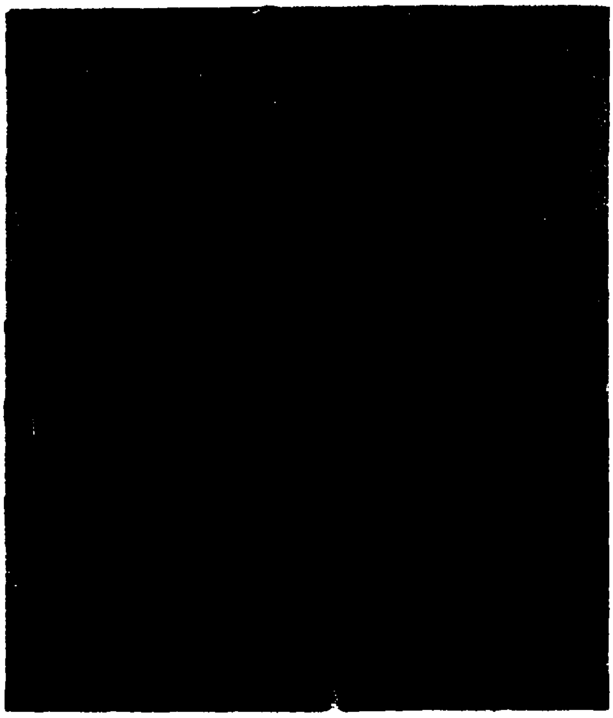


Plate 8. Pot experiment 1962; P toxicity symptoms including cup-shaped leaves in soybeans fertilized with high rates of P and K

1. An increased growth of leaves and stems caused by a strong stimulation of nodulation by P application (Plates 11 and 12). The increased number and weight of nodules presumably resulted in a stronger flow of fixed-N compounds reaching the top of the plants.

2. The concentration of P in the leaves which had deleterious effects on the plant. This may have been a direct P toxicity effect, or may have been caused by entrance of pathogens from outside and their accumulation in the high P-environment of the leaves, or possibly the secretion of toxic substances by the highly stimulated nodule bacteria.

Detrimental effects of high rates of P application accompanied by the symptoms described previously will be referred to hereafter as due to P toxicity although the actual cause of the effects is presently not known.

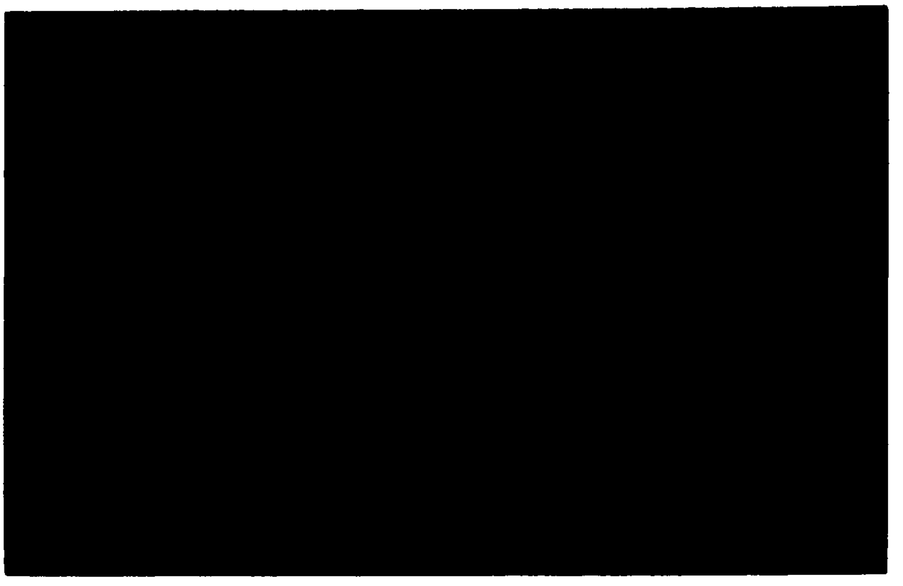
Table 77 shows a strong correlation between the occurrence of leaf symptoms and the percent P in the leaves. All affected plants contained well over 1% P. The K content had no obvious influence and may be either low or high. The number of nodules was higher on those plants receiving P. The numbers were sharply reduced in pots receiving high P alone since many nodules rotted on the severely diseased plants.

2. <u>Growth characteristics as a function of fertilizer input variables</u>

The multiple regression equations relating the dry weight of tops and roots at the growth stage of 4.5 trifoliate leaves to the nutrients applied for each of the two soybean lines in the experiment are given in Table 78. Similar equations for the number and fresh weight of nodules

Plate 9. Pot experiment 1962; from left to right: control and pots receiving high rates of P, P+Ca, P+K and P+K+Ca respectively

Plate 10. Pot experiment 1962; close-up of plants receiving high rates of P+K+Ca



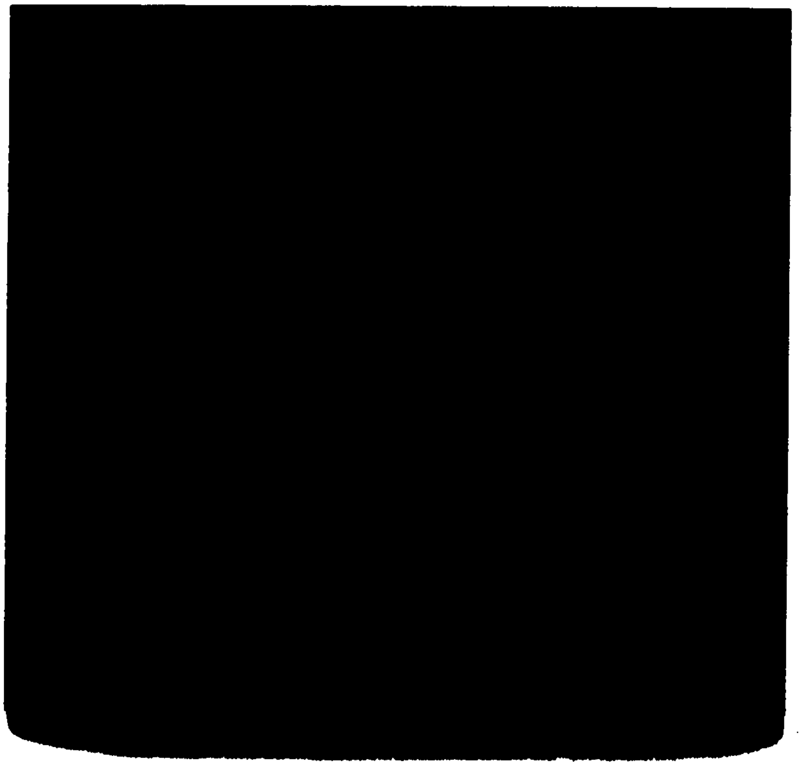


Plate 11. Pot experiment 1962; root system of plants receiving no P

Plate 12. Pot experiment 1962; root system of plants receiving a high rate of P

Table 78. Partial regression coefficients relating the dry weight of tops and roots of two soybean lines, grown in pots in 1962 and harvested at the stage of 4.5 trifoliate leaves, to fertilization; their level of significance and significant differential effects between lines; values of R^2 and experimental error

	Tops				Roots			
Factor	Entry 4 b_i	Entry 5 b_i'	$b_i - b_i'$	*t*	Entry 4 b_i	Entry 5 b_i'	$b_i - b_i'$	*t*
b_o	2.4056**	2.1339**			1.4765**	1.5081**		
P	1.9755**	1.6681**			0.3368**	0.4488*		
K	0.1201	0.2448			0.0157	0.2152		
Ca	-0.0507	0.0917			0.1325	0.1412		
P^2	-0.5395**	-0.3758**	0.1637	2.10*	-0.1514**	-0.1464**		
K^2	-0.0337	-0.0549			0.0056	-0.0364		
Ca^2	-0.0111	-0.0163			-0.0441++	-0.0362		
PK	0.1274*	0.0750+			0.0387++	0.0521+		
PCa	0.1411**	0.0140	0.1271	1.93++	0.0560**	0.0116		
KCa	-0.0109	-0.0253			-0.0124	-0.0350		
PKCa	-0.0149	0.0052			0.0024	0.0109		
R^2	0.8630	0.7606			0.7913	0.6626		
Experimental error			0.2646				0.0643	

Table 79. Partial regression coefficients relating the number and fresh weight of nodules of two soybean lines, grown in pots in 1962 and harvested at the stage of 4.5 trifoliate leaves to fertilization; their level of significance and significant differential effects between lines; values of R^2 and experimental error

Factor	Number of nodules				Fresh weight of nodules			
	Entry 4 b_i	Entry 5 b_i'	b_i-b_i'	$\underline{t}$	Entry 4 b_i	Entry 5 b_i'	b_i-b_i'	$\underline{t}$
b_o	46.1797	14.4469			0.7511	0.2231		
P	268.7889**	207.2102**			2.1783**	2.1933**		
K	55.5101	68.1518+			-0.0642	0.5522+		
Ca	-6.5939	17.2044			0.1791	-0.1168		
P^2	-70.0724**	-46.0891**	23.9833	1.66+	-0.5586**	-0.4822**		
K^2	-6.2529	-12.6906			-0.0037	-0.0864		
Ca^2	-2.3613	-4.7977			-0.0888	0.0127		
PK	17.3048*	11.7828+			0.0205	-0.0310		
PCa	11.9678	-0.3295			0.0941	-0.0146	0.1087	1.51+
KCa	-5.0993	-5.3324			-0.0126	-0.0732		
PKCa	0.0606	-0.5049			0.0250	0.0260		
R^2	0.8426	0.7057			0.7238	0.7057		
Experimental error			8997				0.3157	

are given in Table 79. The values of R^2 were high and F-tests on overall regressions were significant at the 0.01 level of probability.

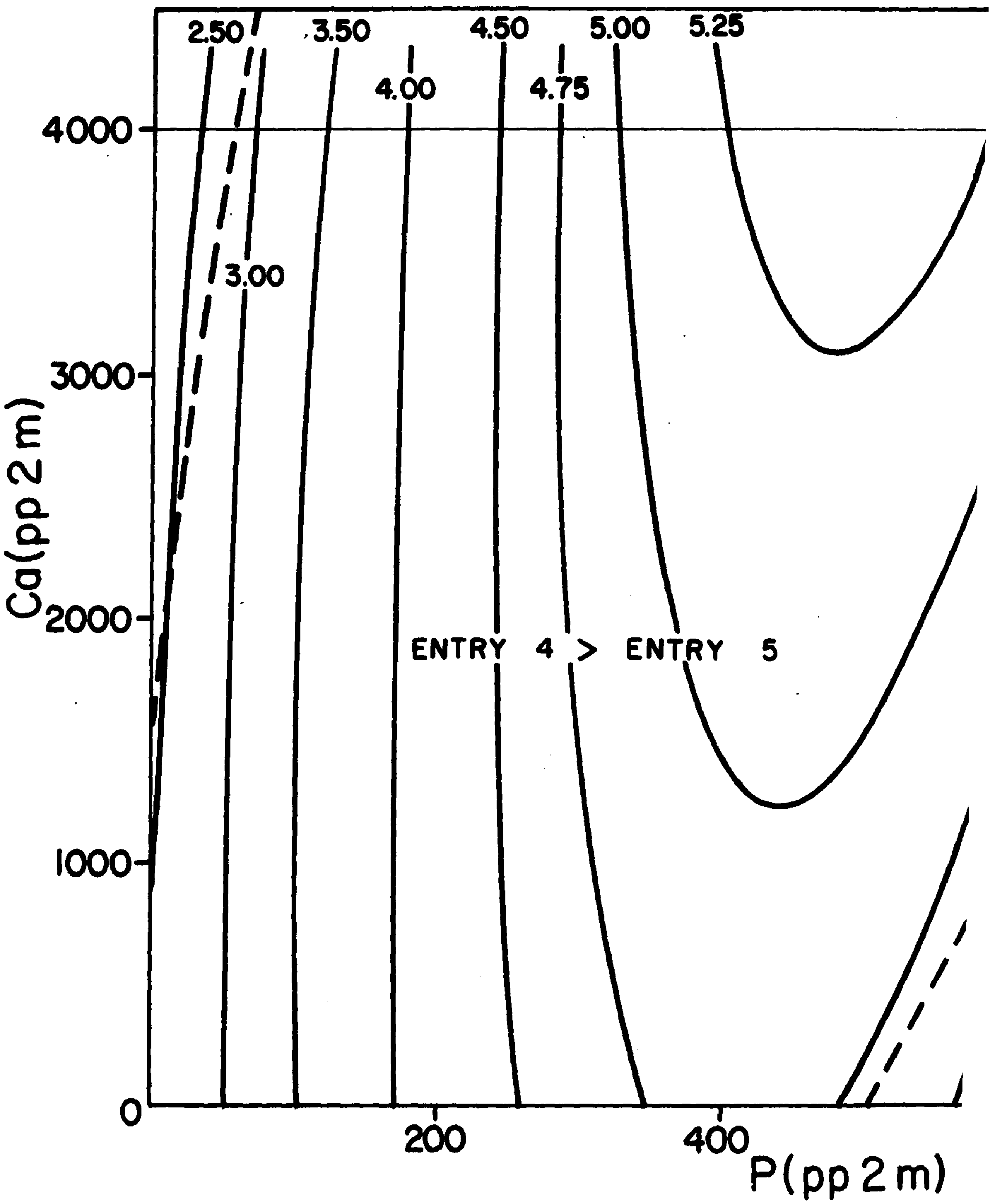
The t-tests on the partial regression coefficients indicated that the fertilizer effects on the production of tops and roots were largely due to P. In the case of Entry 4 the PCa and PK interactions were also involved at the 0.01 and lower levels of significance respectively. Differential responses of top growth among the varieties with respect to P^2 and PCa reached the 0.05 and 0.10 levels of significance. The regression analysis of the number and fresh weight of nodules also indicates highly significant fertilizer effects and again specifies primarily the linear and quadratic effects of P as responsible for the results. The PK interaction affected the number of nodules of Entry 4 significantly also. There was some suggestion of differential effects with respect to P^2 for the number of nodules and to the PCa interaction for the fresh weight of nodules at the 0.20 level of significance (Table 79).

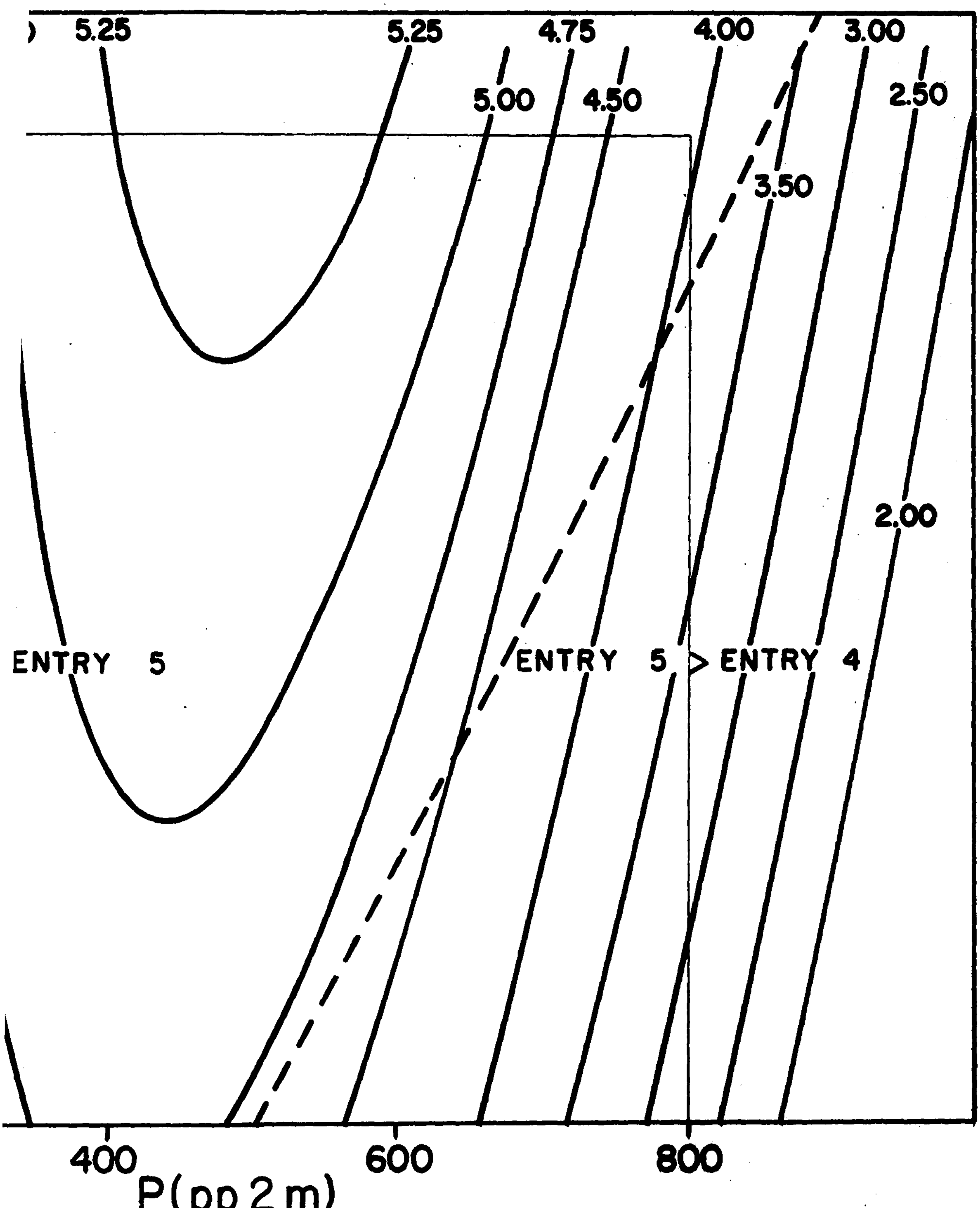
Combination of the multiple regression equations for the purpose of tests on differential responses by Duncan's procedure is not useful since only 2 varieties are involved and Duncan's method reverts to a t-test under those conditions.

Isoquant maps for the dry-weight production of tops and roots show the dependence on P and Ca application when K is held constant at 400 pp2m (Figures 19 and 20). The region of P and Ca combinations resulting in larger weight of tops of Entry 4 is indicated by the projection of the line of intersection between the ellipsoidal surfaces for the two soybean lines on the horizontal plane. Whereas Entry 4 produced more tops in

Figure 19. Isoquants of dry-weight production of tops at the 4.5-leafed stage for Entry 4 in 1962, expressed in grams per pot as a function of P and Ca holding K constant at 400 pp2m and the projection of the line of intersection between the surfaces for Entries 4 and 5

————	Isoquants
— — — —	Projected line of intersection
————	Limits of investigated area

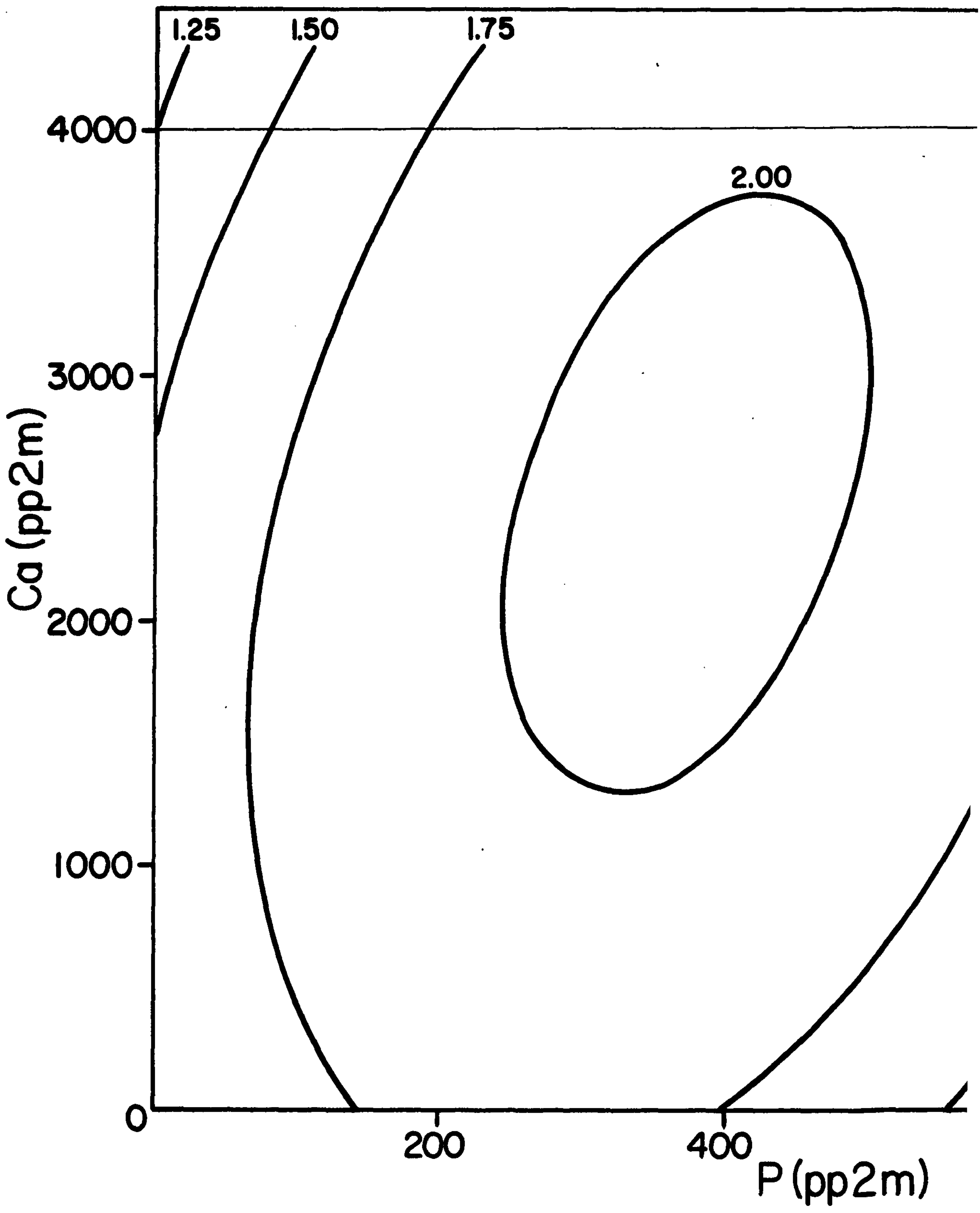

2.50
3.50
4.50
5.00
5.25
4.00
4.75
3.00
4000
3000
2000
1000
0
Ca(pp 2 m)
ENTRY 4 > ENTRY 5
200
400
P(pp 2 m)

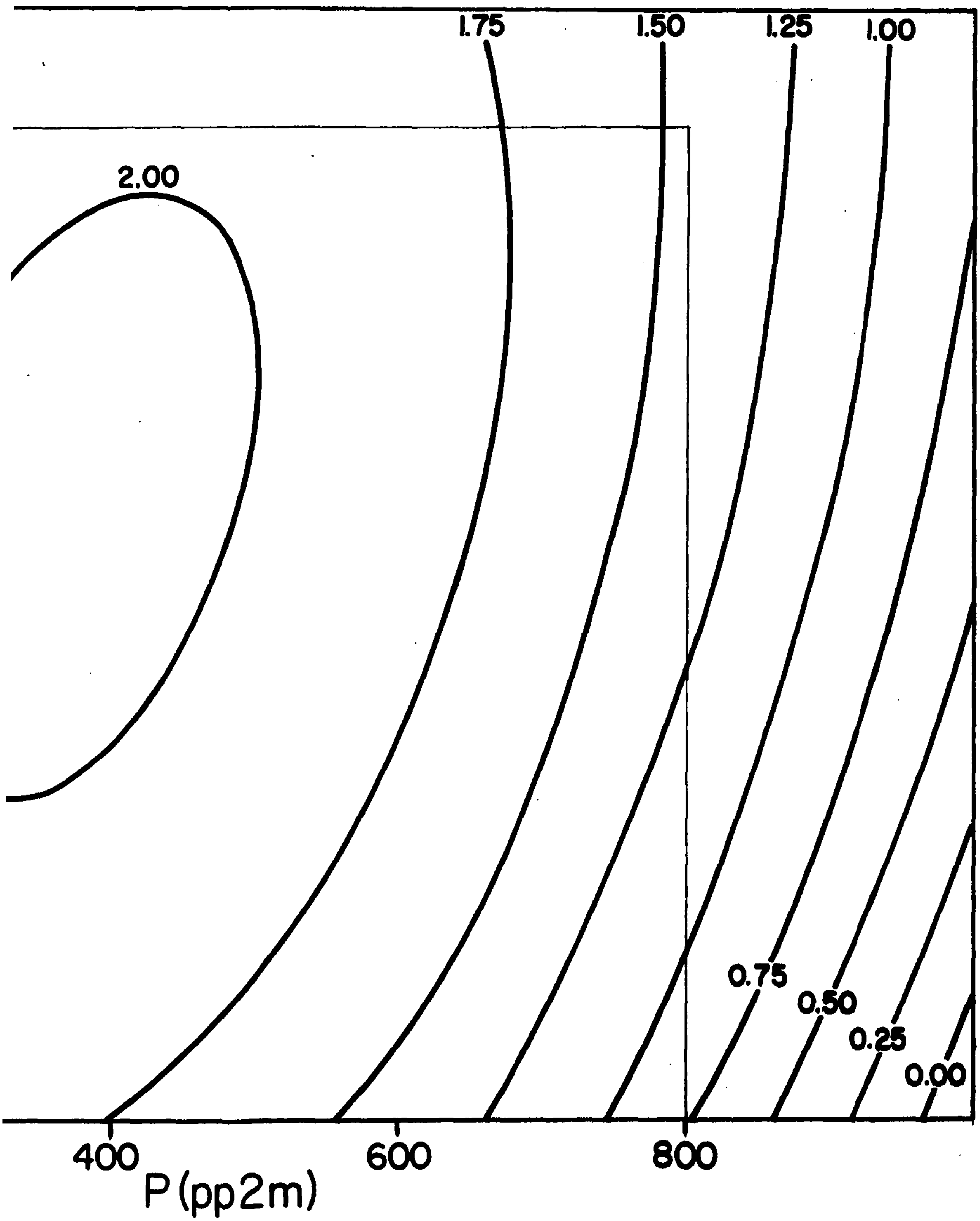


5.25
5.25
4.75
4.00
3.00
5.00
4.50
2.50
3.50
2.00
ENTRY 5
ENTRY 5 > ENTRY 4
400
600
800
P(pp 2 m)

Figure 20. Isoquants of dry-weight production of roots at the 4.5-leafed stage for Entry 4 in 1962, expressed in grams per pot, as a function of P and Ca, holding K constant at 400 pp2m

——————— Limits of investigated area


1.25
1.50
1.75
2.00
4000
3000
2000
1000
0
Ca (pp2m)
200
400
P (pp2m)


1.75
1.50
1.25
1.00
2.00
0.75
0.50
0.25
0.00
400
600
800
P (pp2m)

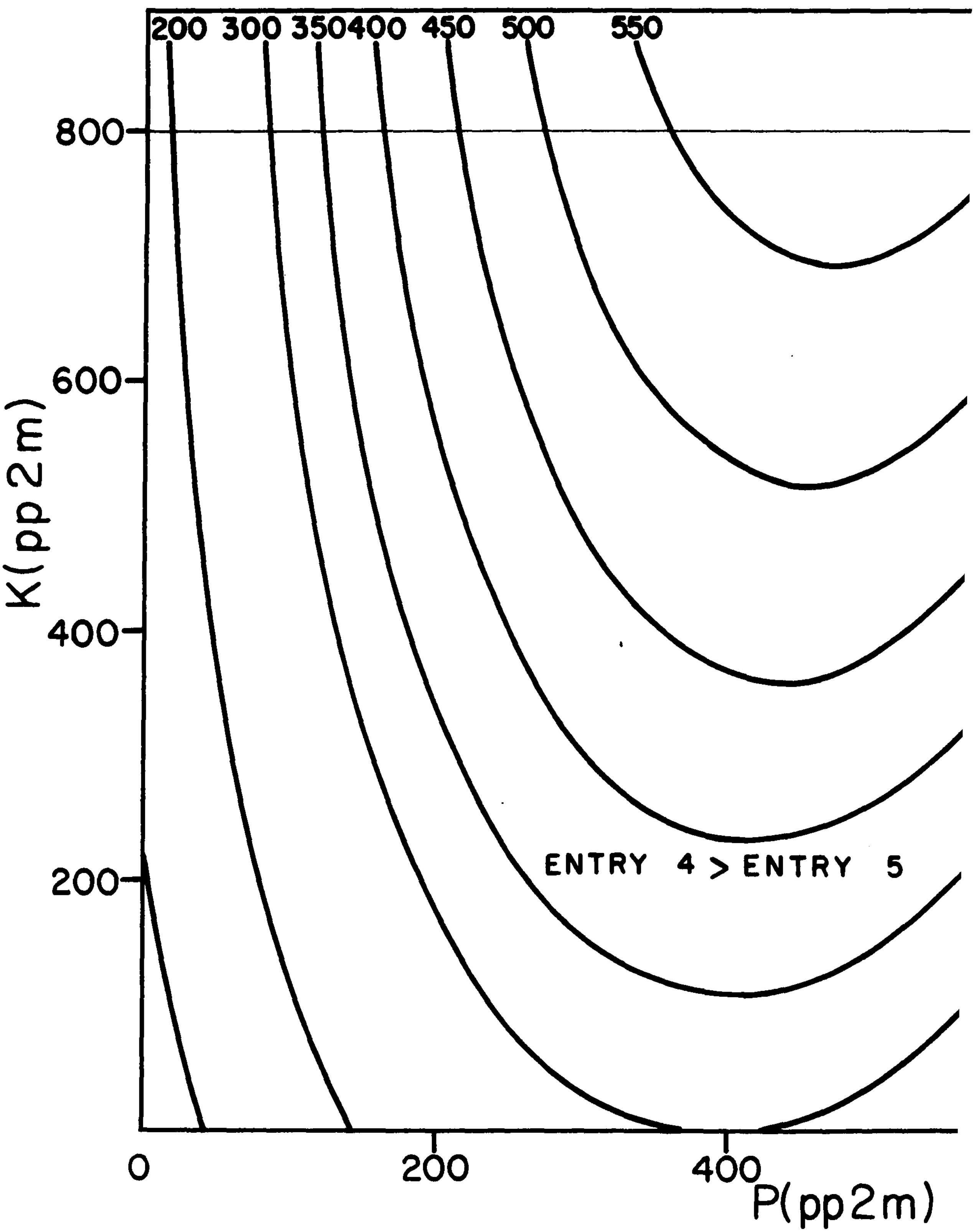
the area of rational production, Entry 5 had a heavier root system at any point in the investigated range of fertilization. Entry 4 also produced more nodules (Figure 21) and this may be a reason for its lighter root system. The elongated shape of the elliptic isoquants in the direction of the ordinate indicates that the effect of P, plotted along the axis was stronger than that of the variables plotted along the ordinate.

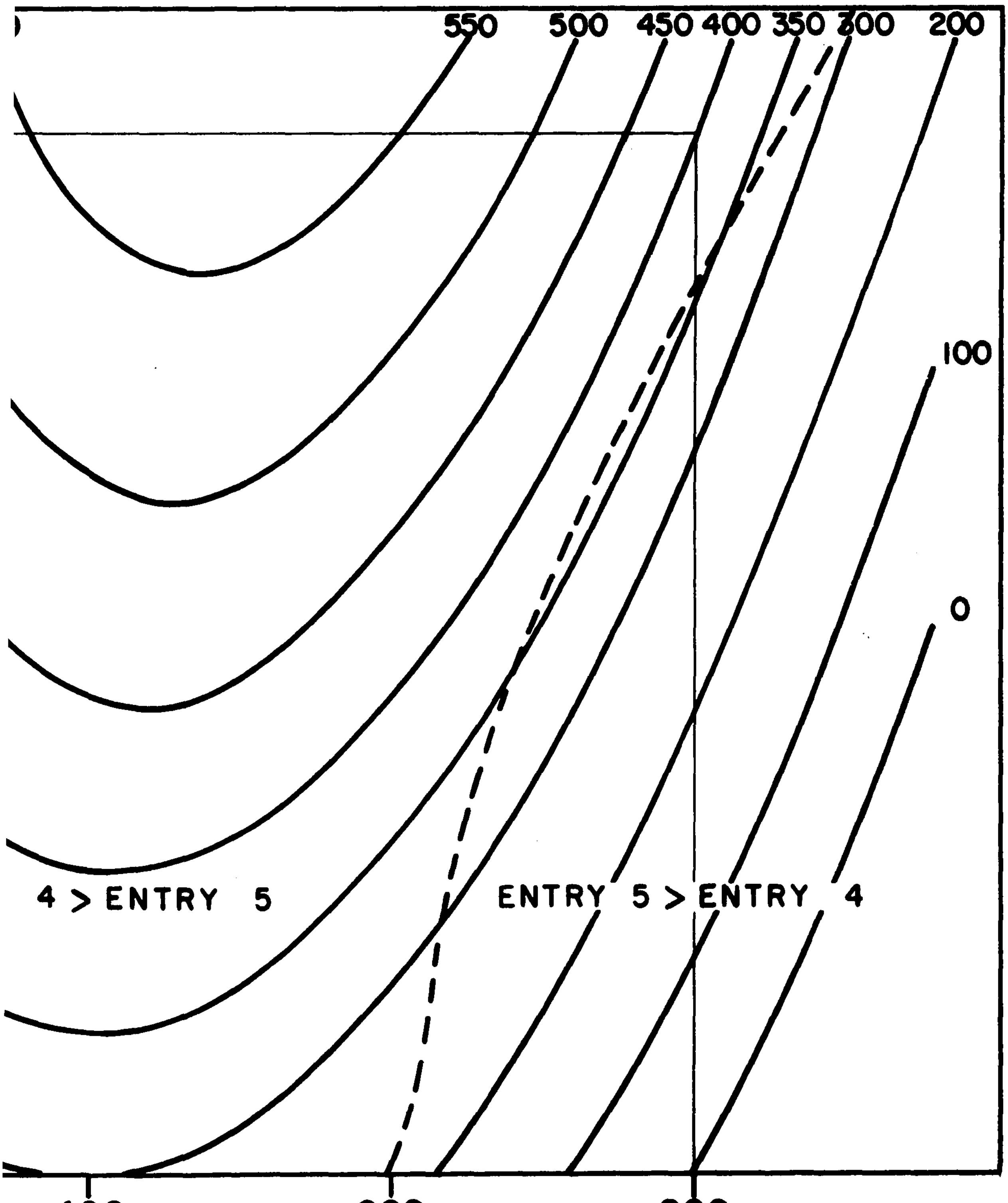
The magnitude of some responses and differential responses which were influenced by factors reaching the 0.20 level of significance or higher was evaluated by graphical interpretation. Ranges of P, K and Ca were selected which would be located in the region of rational production for most dependent variables in this study and would allow a comparison between the results of the various experiments.

The responses of top growth and nodulation characteristics to P were large. Those of the roots were of smaller magnitude. The weight of the tops of Entry 4 was doubled by 300 pp2m and the number and weight of nodules were increased three- and five-fold. Entry 5 was somewhat less responsive. Partial regression coefficients for the dry and fresh weights of leaves, petioles and stems, were also determined and tested for significance. The fresh weights were determined after the pots had been watered and placed inside for a period of two hours. The multiple regression equations for the fresh weights of plant parts allows a comparison of the amount of variation in dry and fresh weights which can be explained by the 10 factors in the model. The weights of the leaves,

Figure 21. Isoquants of number of nodules at the 4.5-leafed stage for Entry 4, grown in pots in 1962, as a function of P and K, holding Ca constant at 0; and the projection of the line of intersection between the surfaces for Entries 4 and 5

━━━━━━━━	Isoquants
━ ━ ━ ━	Projected line of intersection
────────	Limits of investigated area


200
300
350
400
450
500
550
800
600
400
200
K(pp2m)
0
200
400
P(pp2m)
ENTRY 4 > ENTRY 5



550
500
450
400
350
300
200
100
0
4 > ENTRY 5
ENTRY 5 > ENTRY 4
400
600
800
P(pp2m)

Table 80. Magnitude of predicted responses and differential responses of several growth characteristics for two soybean lines, grown in pots in 1962 and harvested at the stage of 4.5 trifoliate leaves, to applied P and K, involving one or more significant effects

Dependent variable	Entry	Factor specification pp2m			Yield			Differential response
		P	K	Ca	from	to	response	
Tops (grams	4	0-300	400	2000	2.30	4.80	2.50	
dry weight	5	0-300	400	2000	2.50	4.38	1.78	0.72
Roots (grams	4	0-300	400	2000	1.65	2.05	0.40	
dry weight)	5	0-300	400	2000	1.80	2.35	0.55	
Nodules	4	0-300	400	0	100	417	317	
(number)	5	0-300	400	0	100	330	230	87
	4	300	0-400	0	280	417	137	
	5	300	0-400	0	217	330	113	
Nodules (grams	4	0-300	400	2000	0.60	3.07	2.47	
fresh weight)	5	0-300	400	2000	0.50	2.70	2.20	0.27

Table 81. Significant values of _t_ of factors affecting fresh and dry weight production of five plant parts for two soybean lines grown in pots in 1962 and harvested at the stage of four trifoliate leaves; and values of R^2

Dependent variable	Entry	b_o	P	K	P^2	K^2	Ca^2	PK	PCa	R^2
Tops										
d.wt.	4	7.00**	7.36**		9.56**			2.62*	2.96**	0.8630
fr.wt.	4	5.73**	5.22**		6.73**			2.23*	2.38*	0.7995
d.wt.	5	5.39**	5.40**		5.78**			1.34+		0.7606
fr. wt.	5	5.75**	5.25**		5.43**			2.10*		0.8038
Leaves										
d.wt.	4	6.86**	6.26**		8.41**			2.21*	3.12**	0.8218
fr.wt.	4	5.93**	4.81**		6.45**			2.14*	2.72*	0.7803
d.wt.	5	5.70**	4.85**		5.30**					0.6984
fr.wt.	5	6.57**	5.08**		5.35**			2.38*		0.8062
Petioles										
d.wt.	4	5.42**	5.60**		7.49**			2.43*	2.16*	0.8058
fr.wt.	4	4.60**	4.31**		5.85**			2.55*	2.23*	0.7507
d.wt.	5	4.28**	4.89**		5.61**			2.40*		0.8061
fr.wt.	5	4.18**	4.55**		4.98**			2.64**		0.8052
Stems										
d.wt.	4	6.52**	7.57**	2.48*	9.61**	2.88**		3.14**	3.21**	0.8927
fr.wt.	4	5.91**	5.62**		6.86**	1.57+		2.28*	2.21*	0.8278
d.wt.	5	3.52**	4.52**		4.47**					0.7061
fr.wt.	5	4.32**	4.98**		4.47**					0.7578
Roots										
d.wt.	4	10.32**	3.02**		6.44**		1.88++	1.91++	2.83**	0.7913
fr.wt.	4	8.47**	4.18**		7.09**		1.83++	1.39	2.99**	0.7915
d.wt.	5	6.38**	2.43*		3.77**			1.56+		0.6626
fr.wt.	5	5.72**	3.30**		4.58**			1.65+		0.6905

petioles and stems were significantly affected by the P, P^2 and PK effects. Entry 4 was also affected by the PCa effect. The t-values of the factors affecting the dry and fresh weights of the plant parts discussed are given in Table 81.

The values of R^2 for the multiple regression of dry and fresh weights were of the same magnitude. The same effects reached significance in both cases with few exceptions and the level of significance of the partial regression coefficients remained largely the same whether dry or fresh weights were employed as dependent variable. It appears therefore that the variation in the fresh weight of any plant part can be explained to no larger extent by fertilizer factors than that of dry weights.

Isoquant maps were produced for the yield of all plant parts harvested at the stage of 4.5 trifoliate leaves. The highest yielding combination of P, K and Ca was approximated by graphical means from a series of isoquant maps for each plant part. The values in Table 82 therefore are approximations only. The optima for P are more reliable because the effects of K and Ca were weak and the location of the optimum was sometimes nearly independent of the level of the last two variables.

The optima for P and K application were relatively high for all parts of the plant. Maximum production for most parts required between 500 and 600 pp2m P. Entry 5 generally had a somewhat higher requirement for P than Entry 4.

Fletcher (1961) also reported a significant effect of P on the number of nodules of a P-tolerant variety (Chief) and a P-sensitive variety

Table 82. Fertilizer combination for maximum yield, maximum yield and ratio of predicted yields at the maximum and at no fertilization for several growth characteristics and two soybean lines grown in pots in 1962 and harvested at the stage of 4.5 trifoliate leaves

Dependent variable	Entry	Combination at maximum (pp2m)[a] P	K	Ca	$\hat{Y}_{max}$	$\hat{Y}_{max} / \hat{Y}_{check}$ (average)
Tops d.wt.	4	510	690	4000	5.50	2.32
(grams)	5	540	750	3000	5.00	
Leaves d.wt.	4	500	800	3100	3.17	2.12
(grams)	5	530	800	2800	2.85	
Petioles d.wt.	4	530	800	3400	0.66	2.62
(grams)	5	590	800	2800	0.65	
Stems d.wt.	4	520	510	4000[b]	1.49	2.66
(grams)	5	560	620	–	1.22	
Roots d.wt.	4	410	800	2500	2.25	1.67
(grams)	5	510	800	2000	2.75	
Nodules	4	550	800	2600	560	22.16
number	5	550	770	0	450	
Nodule fr.wt.	4	510	800	2800	3.60	10.13
(grams)	5	440	560	0	3.40	

[a]When the fertilizer combination for maximum yield was located outside the range of investigation the highest yield of the dependent variable within the investigated range was used as a basis for determination of the combination at the maximum.

[b]Independent of Ca.

(Lincoln) which were grown in pots in the greenhouse. The experiment had 6 rates of P and the maximum number of nodules occurred at 280 pp2m. In another, similar experiment the maximum occurred at 870 pp2m P.

The number of nodules per plant ranged from 12 at no P to 25 at the maximum in one case when the plants had five leaves. In the other trial the maximum number of nodules per plant was 12. These numbers seem too low for normal conditions. In the present study the plants were harvested at a comparable stage (4.5 trifoliate leaves) and the pots were of equal size as those used by Fletcher. The maximum number of nodules was between 450 and 560 per three plants. The average ratio of the predicted yield at optimum fertilization versus unfertilized for the two varieties shows that the maximum response to fertilization is different for various plant parts. The growth characteristics may be placed in order of decreasing response to fertilization as follows:

number of nodules > fresh weight of nodules > stems > petioles > leaves > roots.

This sequence may be considered as existing largely in response to P application since the effects due to P and its interactions with the other elements dominated the responses in this experiment.

The critical percentage composition of the leaves for the production of dry matter of plant tops at the four-leafed stage of development were obtained by substitution of the values of fertilization for maximum yield into the various regression equations describing the variation in the percentage content of the leaves for each nutrient. The results are reported in the next section.

3. Chemical composition of leaves and roots as a function of fertilizer input variables

a. Leaves The model used in previous sections was fitted to the analytical values obtained for the content of five elements in the leaves of plants harvested at the stage of 4.5 trifoliate leaves. All regressions had high F-values testing significant at the 0.01 level of probability. The multiple regression equations for the percent P in the leaves of both varieties showed a highly significant influence of the linear and quadratic effects of P and Ca as well as the PK and PCa interactions (Table 83).

Figure 22 shows the dependence of the percent P on the variables P and Ca for Entry 4 when the applied K is held constant at 400 pp2m. The effect of P is much stronger than that of Ca and the rising rate of increase in percent P with P application is illustrated in the distance between the contour lines. The percent K was affected by the factors K, K^2 and PK at a probability level of 0.01 and by Ca and P at lower levels of significance. The effect of P and K application on the percent K when the applied Ca is held constant at 2000 pp2m is illustrated in Figure 23. The percent Ca in the leaves of both varieties was influenced by the K, Ca and K^2 effect at the 0.05 and 0.01 levels of significance. There was some suggestion of effects due to P^2, Ca^2 and several interactions at the 0.20 level of significance. Figure 24 records the predicted change in percent Ca with varying amounts of P and K while the applied Ca is held constant at 2000 pp2m and shows a minimum percent Ca at 300 pp2m P and 540 pp2m K per acre. The percent Mg was negatively affected by K with both the linear and quadratic K coefficients reaching high significance. Entry 4 was also significantly influenced by the P and PK effects. These relationships are illustrated in Figure 25. Only

Table 83. Partial regression coefficients relating the percentage composition of the leaves of two soybean lines, grown in pots in 1962 and harvested at the stage of 4.5 trifoliate leaves, to fertilization, their level of significance and significant differential effects between lines; values of R^2 and experimental error

Element	Factor	Entry 4 b_i	Entry 5 b_i'	$b_i - b_i'$	t
P(%)	b_o	0.3138*	0.2807*		
	P	0.4418**	0.3391**		
	K	-0.0741	-0.0402		
	Ca	-0.2881**	-0.2364**		
	P^2	0.1252**	0.1017**		
	K^2	0.0172	0.0099		
	Ca^2	0.0624**	0.0515**		
	PK	-0.0721**	-0.0513**		
	PCa	-0.0707**	-0.0399*	0.0308	1.66+
	KCa	0.0042	0.0027		
	PKCa	-0.0007	-0.0082+		
	R^2	0.9696	0.9716		
	Experimental error			0.0209	
K(%)	b_o	1.6456**	1.3765*	0.2691	1.45+
	P	-0.1550+	0.2303++	0.3853	2.66*
	K	0.6401**	0.5679**		
	Ca	-0.2629*	-0.2262*		
	P^2	0.0407+	-0.0529*	0.0936	3.08**
	K^2	-0.1486**	-0.1127**		
	Ca^2	0.0254	0.0418++		
	PK	0.1137**	0.0880**		
	PCa	0.0143	0.0000		
	KCa	0.0347++	0.0193		
	PKCa	-0.0163*	-0.0117++		
	R^2	0.8932	0.8784		
	Experimental error			0.0402	

Table 83. (Continued)

Element	Factor	Entry 4 b_i	Entry 5 b_i'	b_i-b_i'	$\underline{t}$
Ca(%)	b_o	1.9002**	2.1691**	0.2681	2.29*
	P	-0.0168	0.0150	0.0318	3.48**
	K	-0.2020*	-0.3612**	0.1591	1.81⧺
	Ca	0.1766*	0.2241*		
	P^2	0.0296+	0.0103		
	K^2	0.0419*	0.0820**	0.0402	2.09*
	Ca^2	-0.0218	-0.0321+		
	PK	-0.0241+	-0.0188		
	PCa	-0.0024	0.0255+	0.0279	1.72⧺
	KCa	0.0068	-0.0057		
	PKCa	-0.0004	-0.0085+	0.0081	1.47+
	R^2	0.7070	0.7550		
	Experimental error			0.0160	
Mg(%)	b_o	0.6066**	0.6939**		
	P	0.0916*	0.0490		
	K	-0.1725**	-0.1734**		
	Ca	0.0476	0.0571		
	P^2	-0.0042	-0.0063		
	K^2	0.0386**	0.0384**		
	Ca^2	-0.0129+	-0.0132		
	PK	-0.0305**	-0.0142+	0.0163	1.69⧺
	PCa	0.0089	0.0147		
	KCa	-0.0012	-0.0073		
	PKCa	-0.0008	-0.0024		
	R^2	0.8218	0.7461		
	Experimental error			0.0053	
N(%)	b_o	4.8257**	4.5981**		
	P	-0.7122*	-0.8605*		
	K	-0.3307	-0.3729		
	Ca	-0.0154	-0.1621		

Table 83. (Continued)

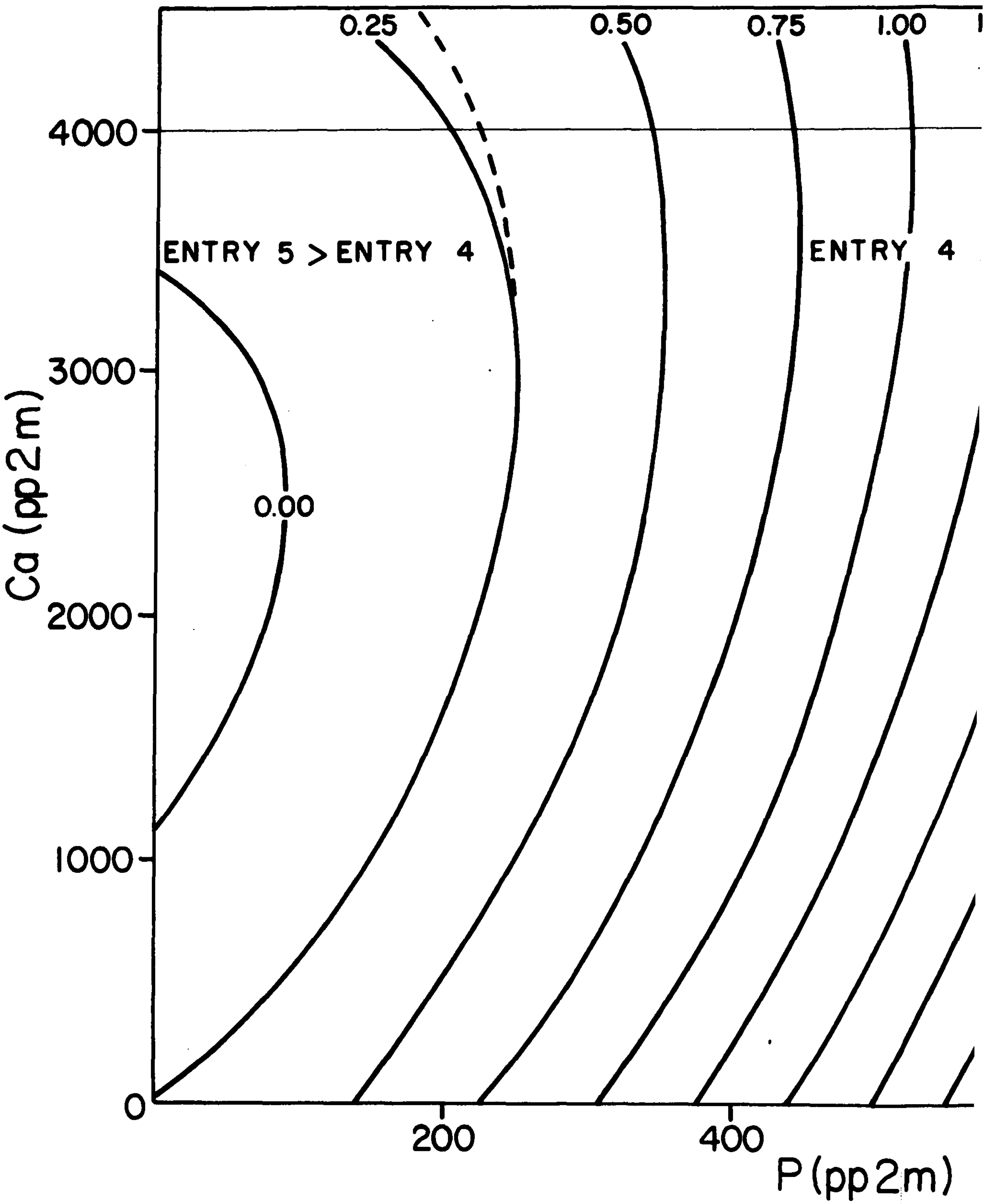
Element	Factor	Entry 4 b_i	Entry 5 b_i'	b_i-b_i'	t
	P^2	0.1929**	0.2365**		
	K^2	0.0186	0.0519		
	Ca^2	0.0084	0.0494		
	PK	-0.0601	-0.0775+		
	PCa	-0.0849+	-0.0384		
	KCa	0.0251	0.0387		
	PKCa	0.0175	-0.0043		
	R^2	0.5293	0.6341		
	Experimental error			0.2025	

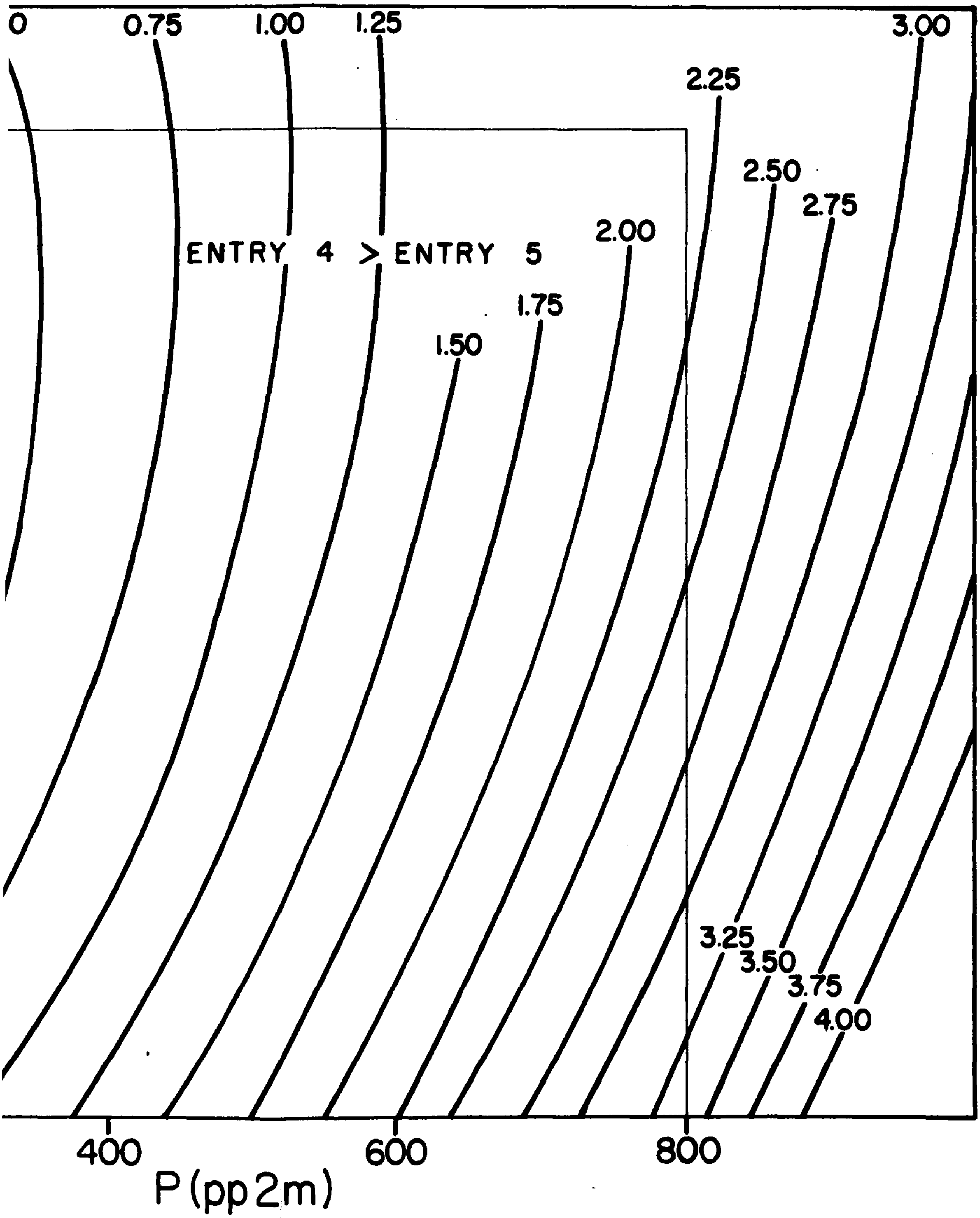
53 to 63% of the variation in percent N in the leaves could be explained by fertilization. All of this was due to the P effect, the linear and quadratic components of which reached the 0.05 and 0.01 levels of significance. The factor P presumably controlled the percent N in the leaves largely by its strong effect on the nodulation of the plant.

Differential effects between the two lines were tested for significance by t-tests using the experimental error obtained from analysis of variance. The most significant differential responses in percentage composition occurred with respect to the percent K and percent Ca in the leaves (Table 83). P and P^2 were significantly different in their effect on the percent K; P and K^2 caused significant differential responses in percent Ca at the 0.05 level, while the K and PCa effects on the two varieties differed at the 0.10 level of significance. Weaker differential responses were found for the percent P and percent Mg in

Figure 22. Contours of percent P in the leaves at the 4.5-leafed stage for Entry 4, grown in pots in 1962, as a function of P and Ca, holding K constant at 400 pp2m; and the projection of the line of intersection between the surfaces for Entries 4 and 5

Contours
Projected line of intersection
Limits of investigated area

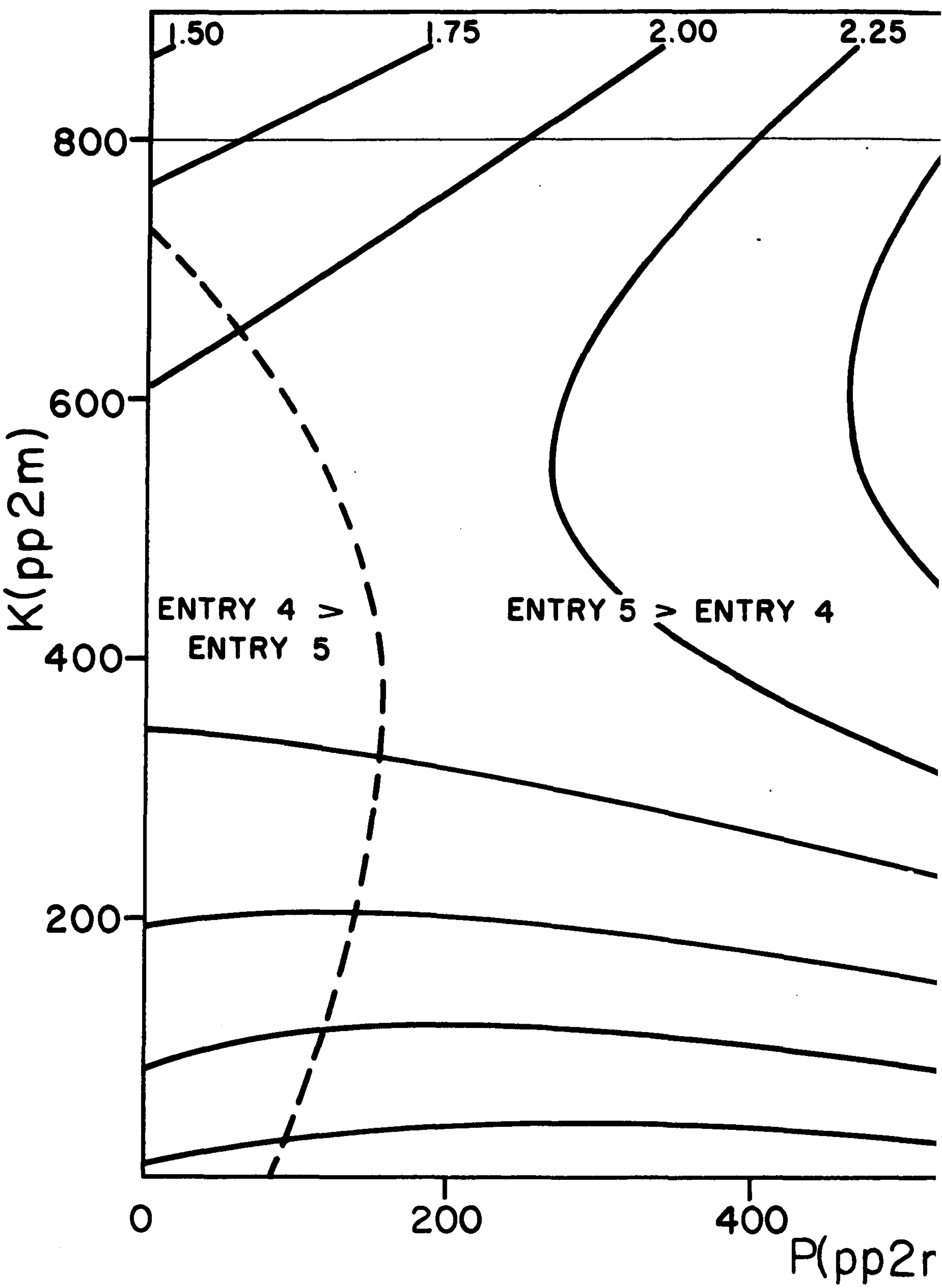

0.25
0.50
0.75
1.00
4000
3000
2000
1000
0
ENTRY 5 > ENTRY 4
ENTRY 4
0.00
Ca (pp2m)
200
400
P (pp2m)

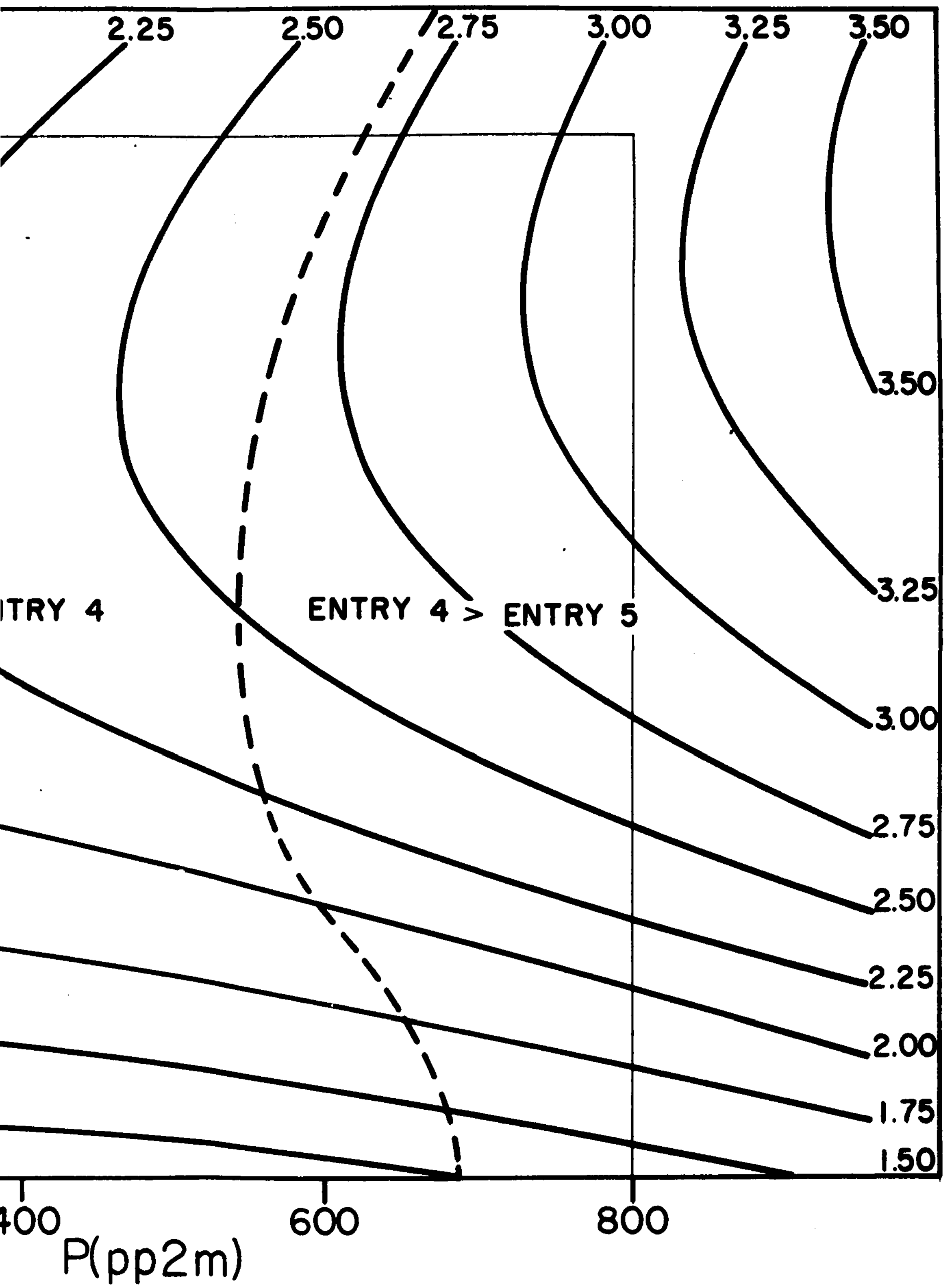


0
0.75
1.00
1.25
2.25
3.00
2.50
2.75
2.00
ENTRY 4 > ENTRY 5
1.75
1.50
3.25
3.50
3.75
4.00
400
600
800
P (pp2m)

Figure 23. Contours of percent K in the leaves at the 4.5-leafed stage for Entry 4, grown in pots in 1962, as a function of P and K, holding Ca constant at 2000 pp2m; and the projection of the line of intersection between the surfaces for Entries 4 and 5

▬▬▬▬▬	Contours
▬ ▬ ▬ ▬	Projected line of intersection
────────	Limits of investigated area

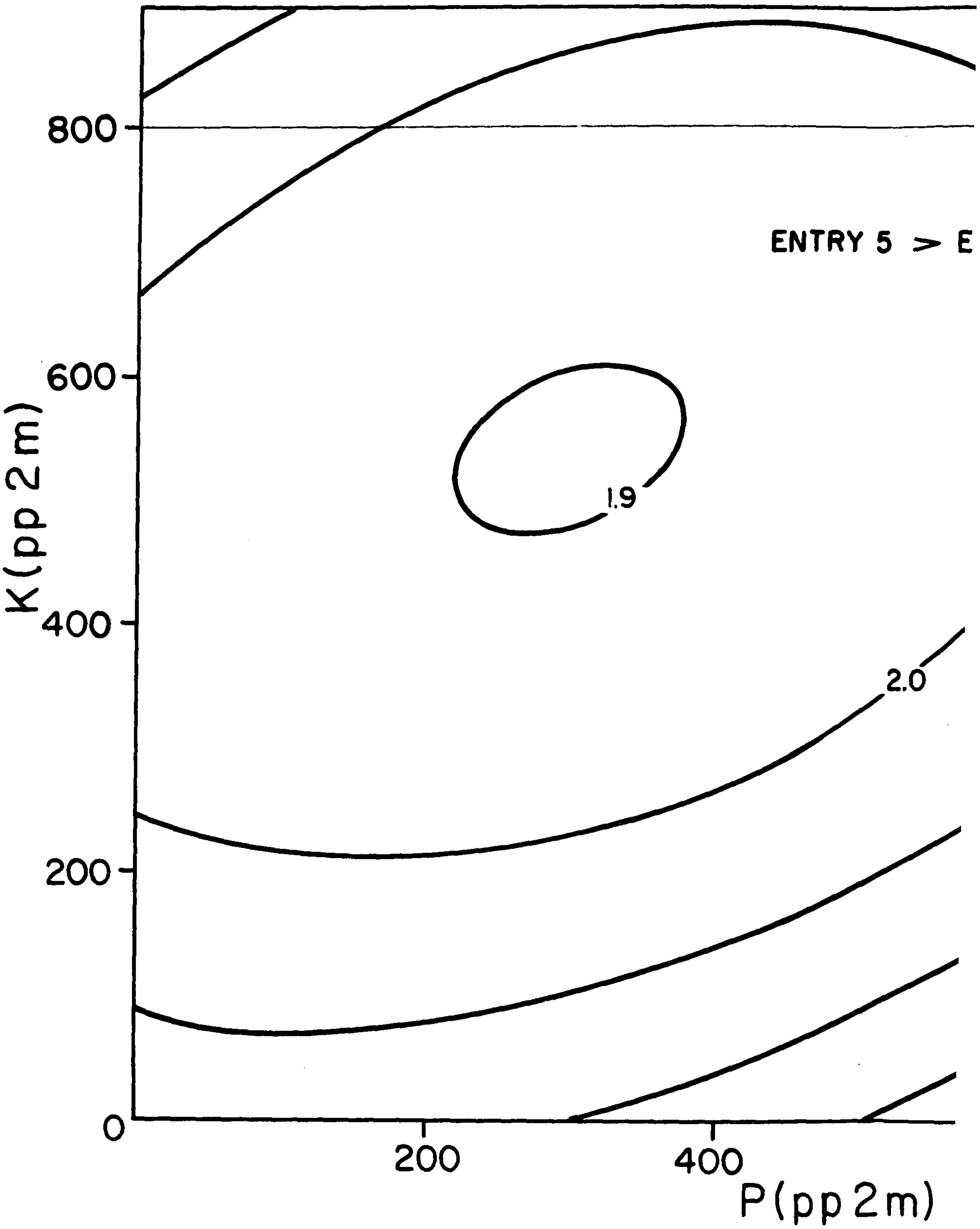

1.50
1.75
2.00
2.25
800
600
400
200
K(pp2m)
ENTRY 4 >
ENTRY 5
ENTRY 5 > ENTRY 4
0
200
400
P(pp2r



2.25
2.50
2.75
3.00
3.25
3.50
3.50
3.25
3.00
2.75
2.50
2.25
2.00
1.75
1.50
ITRY 4
ENTRY 4 > ENTRY 5
400
600
800
P(pp2m)

Figure 24. Contours of percent Ca in the leaves at the 4.5-leafed stage for Entry 4, grown in pots in 1962, as a function of P and K, holding Ca constant at 2000 pp2m; and the projection of the line of intersection between the surfaces for Entries 4 and 5

——— (heavy solid)	Contours
— — — —	Projected line of intersection
——— (thin solid)	Limits of investigated area



ENTRY 5 > E
1.9
2.0
800
600
400
200
0
200
400
K(pp 2m)
P(pp 2m)

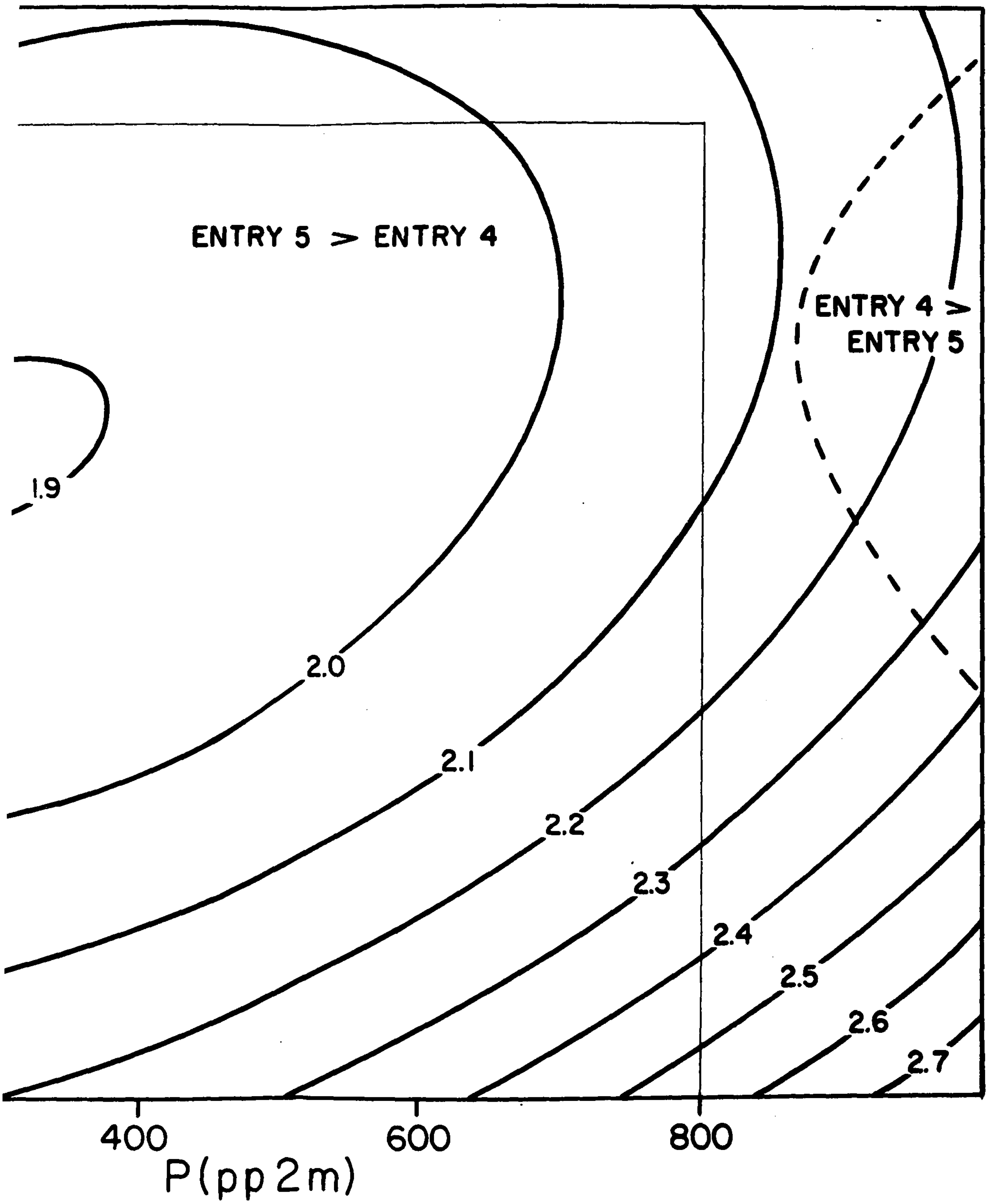
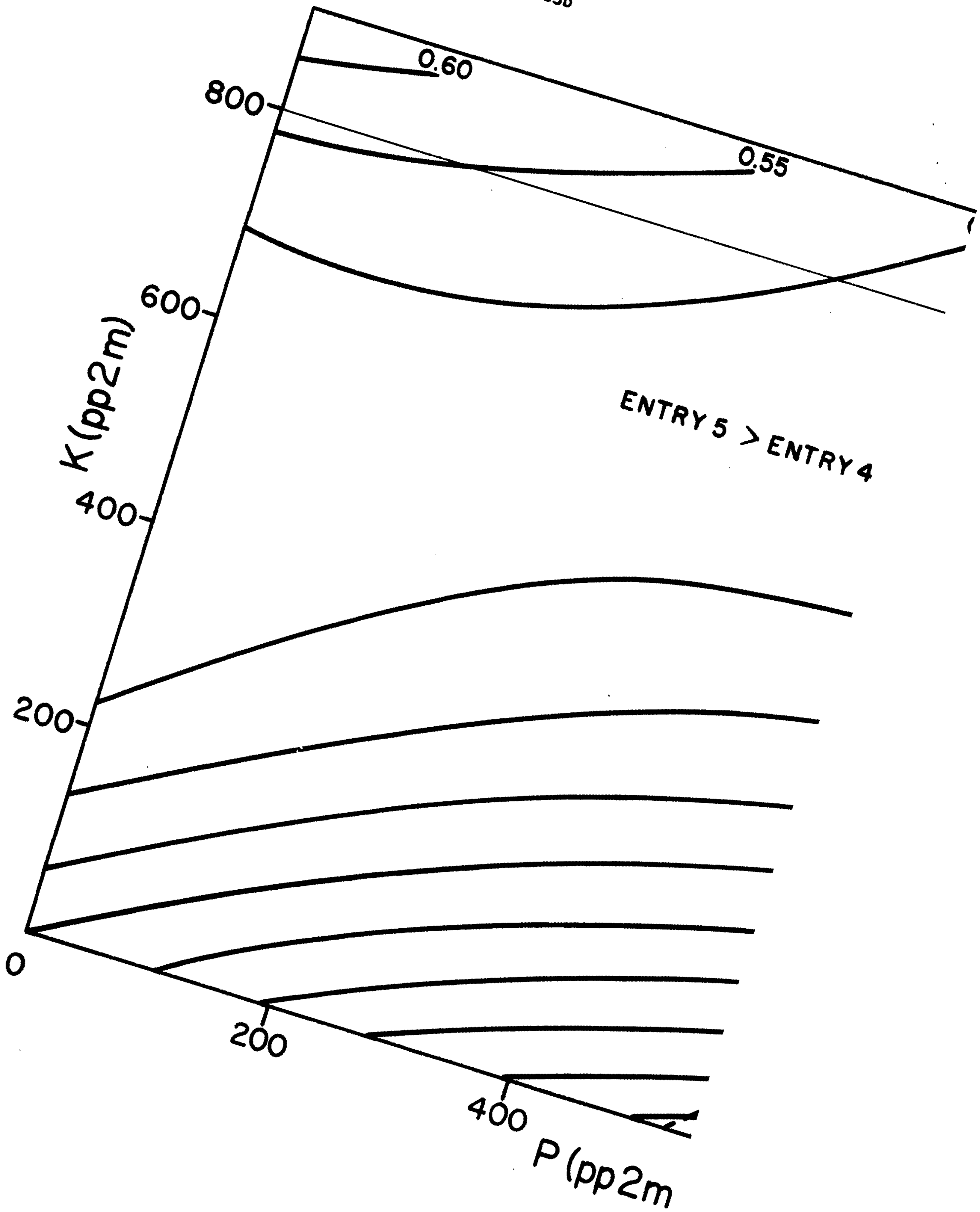
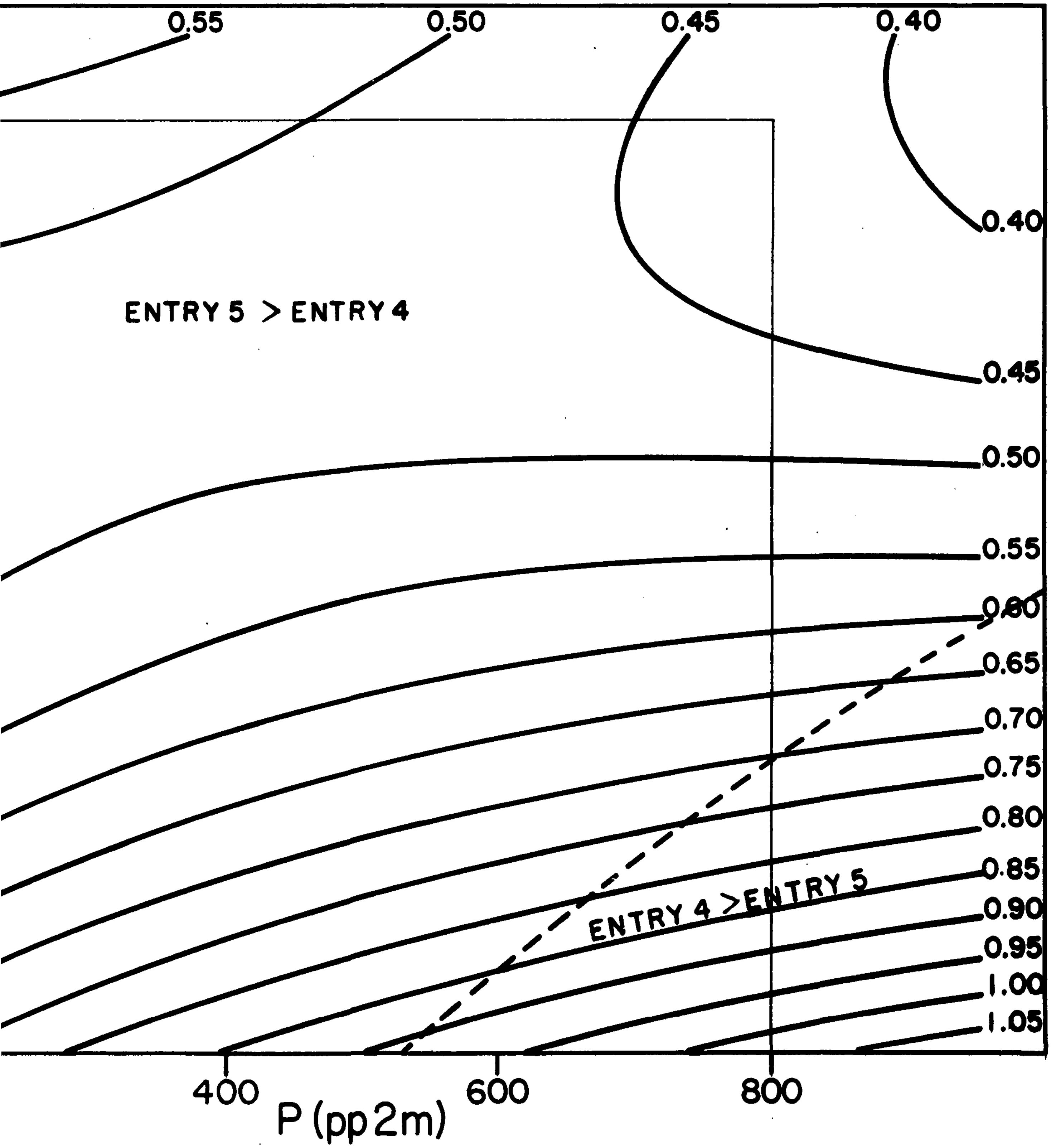

ENTRY 5 > ENTRY 4
ENTRY 4 >
ENTRY 5
1.9
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
400
600
800
P(pp2m)

Figure 25. Contours of percent Mg in the leaves at the 4.5-leafed stage for Entry 4, grown in pots in 1962, as a function of P and K, holding Ca constant at 2000 pp2m; and the projection of the line of intersection between the surfaces for Entries 4 and 5

——— (heavy solid line)	Contours
— — — — (heavy dashed line)	Projected line of intersection
——— (thin solid line)	Limits of investigated area

183b





0.55
0.50
0.45
0.40
0.40
0.45
0.50
0.55
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.95
1.00
1.05
ENTRY 5 > ENTRY 4
ENTRY 4 > ENTRY 5
400
600
800
P (pp2m)

the leaves, while none existed for the percent N among the 2 introduced soybean lines.

Contour maps for the percentage nutrient content of the leaves delineate the region of fertilization over which one of the varieties had a higher content of nutrients than the other as a result of variety effects and differential responses. It appears that neither variety had a higher content of any nutrient over the full investigated region. Entry 5 was higher in percent P only at low rates of P application (Figure 22). The projected lines of intersection between the hyperbolic surface for the percent K of Entry 4 and the ellipsoid for Entry 5 shows that the former had a higher K content at low and at very high rates of P application (Figure 23). Entry 5 had a higher Ca content over the investigated region (Figure 24). Its leaves also contained more Mg than Entry 4 except in the area leading to P toxicity symptoms (Figure 25). This graph also illustrates the influence of K fertilization on the Mg content and the fact that the percent Mg was reduced by application of P at high levels of K but raised by P at low levels of K.

The magnitude of the predicted responses measured over the same range of fertilizers applied as in previous sections is given in Table 84. The response of the percent P to 300 pp2m P is positive and large; that to 2000 pp2m Ca is negative and equally large. The average increase in percent K due to an application of 300 pp2m P is 0.3 at the levels chosen for the other elements and the effect of 2000 pp2m Ca is of the same order but negative. The decrease in percent Ca due to 400 pp2m K is of the same order as the raise in percent Ca from the 2000 pp2m Ca

Table 84. Magnitude of predicted responses and differential responses of leaf composition of two soybean lines, grown in pots in 1962 and harvested at the stage of 4.5 trifoliate leaves to applied P, K and Ca, involving one or more significant effects

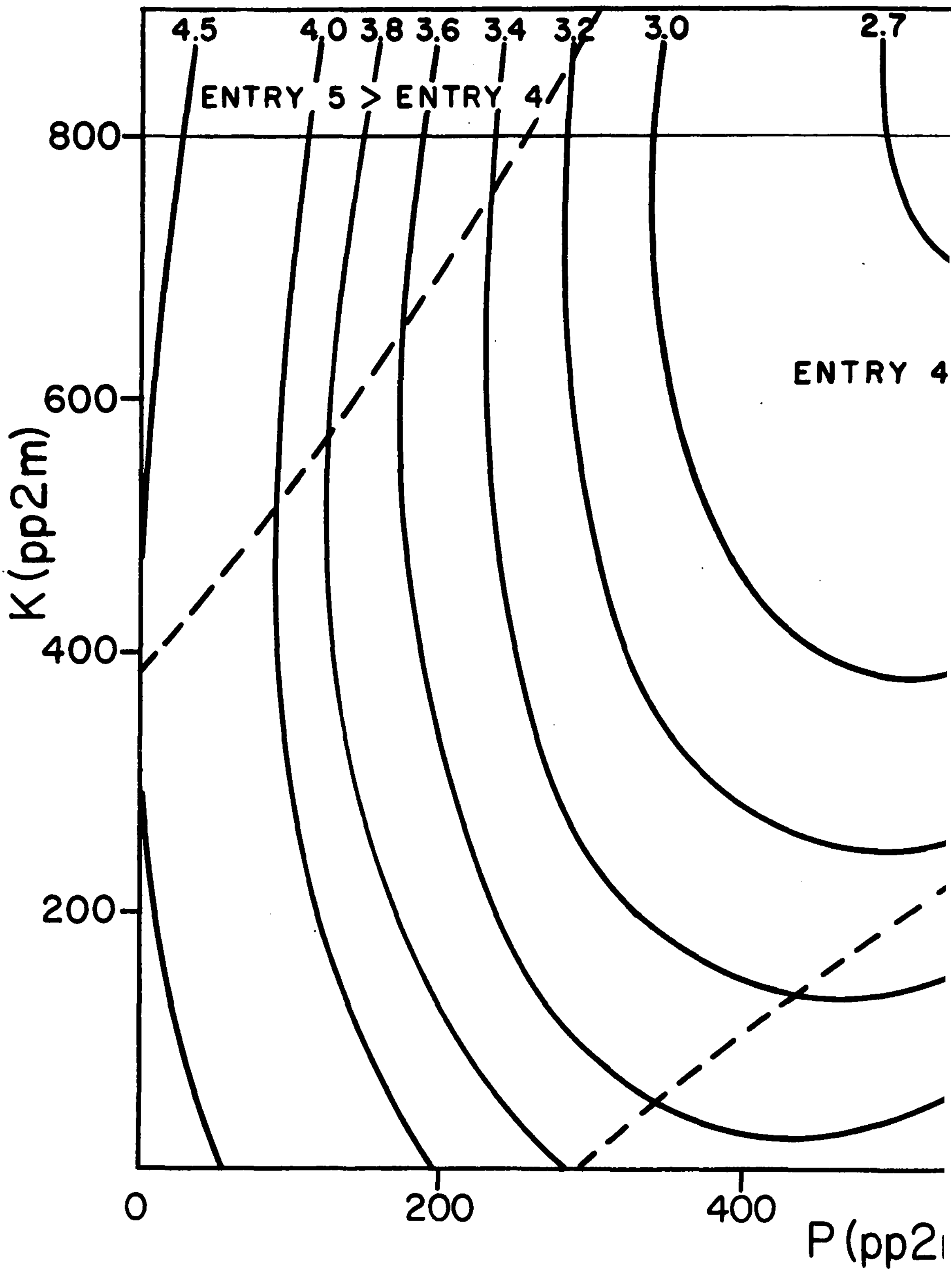
Dependent variable	Entry	Factor specification (pp2m)			Percentage			Differential response
		P	K	Ca	from	to	response	
%P	4	0-300	400	2000	0	0.45	0.45	
	5	0-300	400	2000	0	0.41	0.41	0.04
	4	300	400	0-2000	1.00	0.45	-0.55	
	5	300	400	0-2000	0.86	0.41	-0.45	0.10
%K	4	0-300	400	2000	2.00	2.20	0.20	
	5	0-300	400	2000	1.85	2.25	0.40	0.20
	4	300	0-400	2000	1.05	2.20	1.15	
	5	300	0-400	2000	1.30	2.25	0.95	
	4	400	400	0-2000	2.62	2.27	-0.35	
	5	400	400	0-2000	2.67	2.33	-0.34	
%Ca	4	300	0-400	2000	2.22	1.93	-0.30	
	5	300	0-400	2000	2.63	2.09	-0.54	0.24
	4	400	400	0-2000	1.65	1.93	0.28	
	5	400	400	0-2000	1.75	2.10	0.35	
%Mg	4	300	0-400	2000	0.82	0.52	-0.30	
	5	300	0-400	2000	0.87	0.58	-0.29	
%N	4	0-300	400	2000	4.35	3.40	-0.95	
	5	0-300	400	2000	4.10	2.97	-1.13	

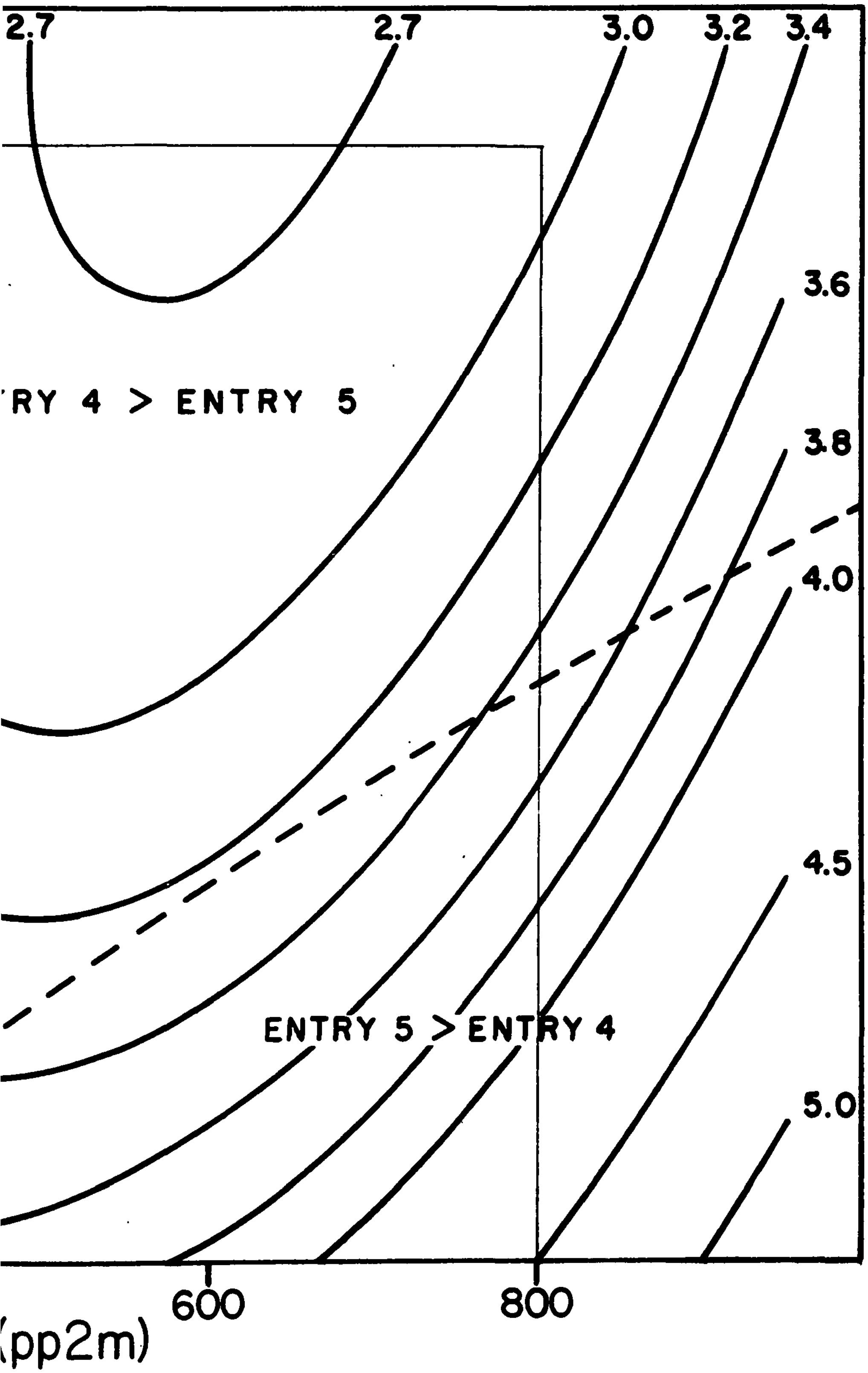
applied. And the decrease in percent Mg due to 400 pp2m K is of the same magnitude as that in percent Ca under the same treatment, but this affects the total amount of Mg in the plant more drastically than it does that of Ca. The percent N is reduced strongly by P application (Figure 26). The total amount of N in the leaves, however, rose from 6.09 to 9.18 milligrams for Entry 4 and from 6.15 to 7.57 milligrams for Entry 5.

The nutrient content of the leaves was also computed on a total and on a fresh-weight percentage basis. The fraction of the variation in the data which can be explained by fitting the same model and the *t*-values of the partial regression coefficients were tabulated to decide upon the most advantageous form in which to express the chemical composition data (Table 85). Comparing the *t*-values for the partial regression coefficients of the equations for the dry-weight and fresh-weight percentages of each nutrient it may be seen that the differences between them are small and the levels of significance very similar in the two cases. The values of R^2 indicate that the portion of the variation which can be accounted for is no larger for fresh-weight than for dry-weight percentage composition. The expression of the chemical composition as total content of nutrient in the leaves leads to different conclusions for the individual nutrients. The values of *t* for the total P content are small and the significance levels sharply reduced compared to those expressed on a percentage basis. Also the total amount of variation explained is somewhat lower. The variation in total amount of K in the leaves can be explained equally well as that of percentage contents.

Figure 26. Contours of percent N in the leaves at the 4.5-leafed stage for Entry 4, grown in pots in 1962, as a function of P and K, holding Ca constant at 4000 pp2m; and the projection of the line of intersection between the surfaces for Entries 4 and 5

Contours
Projected line of intersection
Limits of investigated area


4.5
4.0
3.8
3.6
3.4
3.2
3.0
2.7
ENTRY 5 > ENTRY 4
ENTRY 4
800
600
400
200
K (pp2m)
0
200
400
P (pp2


2.7
2.7
3.0
3.2
3.4
3.6
3.8
4.0
4.5
5.0
RY 4 > ENTRY 5
ENTRY 5 > ENTRY 4
600
800
(pp2m)

The distribution of significant factors, however, is altered considerably. The t-values of the coefficients for Ca, K and K^2 were reduced in size and the significance of Ca was lost by expressing the K content on a total basis. The P and P^2 effects on the other hand gained in significance. The gain in significance was presumably caused by introduction of the dry-weight of the leaves as a product with the percent K, since the leaf production was strongly affected by P application as shown before. Using total K in the leaves may be meaningful in certain cases and would lead to different conclusions to those obtained using percentage or relative concentration values. A similar difference existed in the dependence of total and percentage content of Ca on fertilizer factors. The level of significance of the Ca, K and K^2 effects was reduced in the multiple regressions for total Ca in return for highly significant P and P^2 effects. In the multiple regression for total Mg also the PK interaction effect was lost and the value of R^2 was considerably lower than in the case of percentage contents.

From the evidence above it was decided to use chemical composition data expressed on a dry-weight basis in the discussion of results where possible.

Several relationships contained in the contour maps were summarized in Table 86. It may be seen from this table that the maximum nutrient content of the leaves was limited by the upper limit of P applied for every element except the percent N. The maximum P content required the absence of K and Ca materials. Antagonism of K versus Ca and K versus Mg was expressed in the fertilizer combinations required for maximum

Table 85. Significant values of t for factors affecting the leaf composition expres content basis for two soybean lines, grown in pots in 1962 and harvested

Dependent variable	Entry	b_o	P	K	Ca	P^2	K^2
Dry-weight %P	4	2.34*	4.22**		2.86**	5.68**	
	5	2.63*	4.08**		2.96**	5.81**	
Total P	4	1.47+	1.67+				
	5	1.64+	3.28**		1.44+	3.04**	
Fresh-weight %P	4	1.92++	4.38**		2.54*	4.55**	1.58+
	5	2.41*	4.96**		2.73**	4.33**	
Dry-weight %K	4	10.93**	1.32+	5.65**	2.33*	1.65+	5.99**
	5	9.29**	1.99++	5.10**	2.04*	2.18*	4.62**
Total K	4	4.96**	3.62**	3.40**	1.36+	4.71**	3.66**
	5	2.99**	4.16**	2.88**		4.61**	2.78**
Fresh-weight %K	4	9.61**		4.35**	2.07*		4.01**
	5	7.11**	1.99++	3.23**	1.36+	2.30*	2.86**
Dry-weight %Ca	4	18.69**		2.64*	2.32*	1.77+	2.50*
	5	17.52**		3.88**	2.42*		4.02**
Total Ca	4	5.44**	4.91**	1.88++	1.84++	6.36**	1.94++
	5	5.50**	4.84**	1.64+	1.89++	5.05**	1.76++
Fresh-weight %Ca	4	15.75**		3.37**	2.08*		4.09**
	5	11.98**		3.39**	1.76++		3.41**
Dry-weight %Mg	4	10.60**	2.05*	4.01**			4.09**
	5	11.26**		3.74**			3.78**
Total Mg	4	3.81**	3.66**	2.89**	1.47+	4.50**	2.96**
	5	5.57**	4.68**	2.72*	1.75++	4.89**	2.73**
Fresh-weight %Mg	4	10.36**	2.71*	4.70**			5.30**
	5	13.63**	1.46+	5.22**	1.66+		5.18**

ition expressed on a dry-weight percentage, fresh-weight percentage and a total
d harvested at the stage of 4.5 trifoliate leaves; and values of R^2

K^2	Ca^2	PK	PCa	KCa	PKCa	R^2
	2.83**	3.80**	3.81**			0.9696
	2.94**	3.40**	2.70*		1.63+	0.9716
		1.85++	2.07*		2.36*	0.8712
	1.34+					0.9507
1.58+	2.66*	4.40**	3.96**			0.9600
	2.76**	5.01**	3.22**			0.9648
5.99**		5.34**		1.74++	2.29*	0.8932
4.62**	1.72++	4.20**			1.68++	0.8764
3.66**		4.63**	1.62+			0.8764
2.78**		3.44**				0.8375
4.01**		3.76**			1.76++	0.8420
2.86**		2.04**				0.7391
2.50*		1.68+				0.7070
4.02**	1.57+		1.49+		1.45+	0.7550
1.94++	2.01++	1.37+	3.29**			0.7819
1.76++	1.64+					0.6970
4.09**		2.73**	1.36+			0.7201
3.41**		1.37+				0.6490
4.09**	1.37+	3.76**				0.8218
3.78**		1.63+	1.72++			0.7461
2.96**	1.92++		2.92**			0.6763
2.73**	1.87++					0.6836
5.30**		4.54**				0.8387
5.18**		2.58**				0.8185

Table 86. Fertilizer combinations required for the maximum percentage content of nutrients in the leaves within the investigated region of fertilization and predicted range of nutrient content of the leaves of two soybean lines, grown in pots in 1961 and harvested at the stage of 4.5 trifoliate leaves

Dependent variable	Entry	Fertilizer combination pp2m			Range	
		P	K	Ca	Check	Max.
%P	4	800	0	0	0.31	4.13
	5	800	0	0	0.28	3.30
%K	4	800	720	0	1.65	3.70
	5	800	770	0	1.38	3.33
%Ca	4	800	0	3800	1.90	2.63
	5	800	0	4000	2.17	3.18
%Mg	4	800	0	3100	0.61	1.04
	5	800	0	3700	0.69	1.04
%N	4	0	0	4000	4.83	4.90
	5	0	0	4000	4.60	4.75

percentages of K, Ca and Mg. Table 86 also shows that the range of percent P and percent K in the leaves was very wide in this experiment.

The highest N content occurred in both lines at no P or K and at 4000 pp2m Ca applied. This observation is not meaningful because almost the same content of N is predicted for the fertilizer combinations 0 P, 800 pp2m K and 800 pp2m P, 0 K for Entry 5 (Figure 26).

All three treatment combinations were represented in the experiment. The first two showed restricted growth because no P was included in the treatment. The third point involved the combination of high rates of P and Ca, without K application. Here the growth was restricted by P toxicity. More growth was made than at the other two points, however, and it appears that the increased N-fixation by the nodules was just balanced by the dilution effect from increased growth. More meaningful is the location of a minimum percent N in the investigated range. A minimum of 2.95% N was estimated for Entry 4 and occurred at 540 pp2m P, 800 pp2m K and 4000 pp2m Ca per acre. For Entry 5 a minimum of approximately 2.60% occurred at 580 pp2m P, 800 pp2m K and 4000 pp2m Ca per acre. The estimates were found by graphical interpretation of Figure 26. In this figure the amount of Ca applied was held constant at 4000 pp2m. The minimum is actually located at 2000 pp2m and the values for P and K would require a slight correction for this reason.

It is interesting to note that the location of the minima for %N practically coincided with the maxima for the dry weight of tops and the number and weight of nodules (Table 82).

The critical percentage of each nutrient in the leaves of each line for the production of dry matter of plant tops at the 4.5 leafed stage of development was calculated using the multiple regression equations given in Table 83 and the combinations of P, K and Ca for each variety given in Table 82.

The critical percentages for P and K in Table 87a are high as may be expected at this early stage of development. A downward trend in the chemical composition of soybean tops with progressing stage of development was already described by Hammond _et al_. (1951). Critical percentages should be established ideally for one nutrient while all others are in optimum supply. In practice this condition may not be satisfied,

Table 87a. Critical percentages of P, K and Ca in the leaves of two soybean lines for dry matter production of plant tops at the stage of 4.5 trifoliate leaves and associated leaf contents of Mg and N

Entry	%P	%K	%Ca	%Mg	%N
4	0.73	2.36	2.05	0.44	2.99
5	0.62	2.61	2.16	0.54	2.50

especially in experiments with soil as a medium and having only the 3 elements P, K and Ca as variables. This design, however, approaches the requirements for unbiased critical percentages better than the majority of experiments in the literature with one element as variable and an "adequate supply" of other nutrients. On the other hand the design has the advantage of determining the content of P, K and Ca of the leaves by simultaneously varying the rates of P, K and Ca in one experiment. The critical values found will depend on the level of all other nutrients in the leaves. If any other elements were in somewhat short supply the predicted critical values for the percent P and percent K would include the amount by which P and K application can substitute for some other nutrient in obtaining the maximum yield of tops in the experiment. The values reported are approximations only and the true critical percentages may be somewhat lower than those reported here for P and K.

The N content of the leaves at maximum yield of dry matter was equal to the predicted minimum N content in the investigated area. The fact that the yield of dry matter was maximal at the fertilizer combination leading to optimal nodulation stresses the overriding importance of the symbiotic relationships for legume production. The fact that the content N was at a minimum at maximum yield of dry matter suggests that the N supply, or some factor highly correlated with it, was the limiting factor for soybean growth despite a presumably maximal output of bacterium-fixed N at this point. It may be reasonable to expect that at a P application which is less than optimal for nodulation, the nodule activity is reduced and that the N supply then available would be utilized to the same minimal content as prevailing at maximum yield. The fact that the %N increased suggests that P, or some other element or condition controlled by P, became more limiting than N, unless the apparent relation is a corollary of employing quadratic polynomial models, not reflecting the true shape of the response surface.

b. Roots   Inspection of the partial regression coefficients in Table 87b shows that the percent P of the roots was affected by the same factors as that of the leaves. The factors are P and Ca, their squares and interaction. The significance of the P effects reached the 0.01 level and other effects reached lower levels of significance. The P^2 and PK effects were insignificant in the case of Entry 5. Figure 27 illustrates the strong P effect which increased in magnitude with higher rates of P.

The percent K was largely affected by K and Ca. The factor P was involved as a highly significant PK interaction. The contours of the percent K as a function of P and K in Figure 28 are similar to those for the leaves.

Table 87b. Partial regression coefficients relating the percentage composition of the roots of two soybean lines grown in pots in 1962 and harvested at the stage of 4.5 trifoliate leaves to fertilization; their level of significance and significant differential effects between lines; values of R^2 and experimental error

Element	Factor	Entry 4 b_i	Entry 5 b_i'	$b_i - b_i'$	$\underline{t}$
P(%)	b_o	0.1399++	0.1853*		
	P	0.2872**	0.4376**	0.1504	2.28*
	K^2	0.0482	-0.0098		
	Ca	-0.1008++	-0.1604*		
	P^2	0.0707**	0.0187	0.0520	3.74**
	K^2	-0.0102	0.0011		
	Ca^2	0.0170+	0.0342*		
	PK	-0.0258*	-0.0106		
	PCa	-0.0217*	-0.0256*		
	KCa	-0.0007	-0.0021		
	PKCa	-0.0013	0.0003		
	R^2	0.9796	0.9656		
	Experimental error			0.00834	
K(%)	b_o	1.3151**	1.6147**		
	P	-0.0856	0.1365		
	K^2	0.7405**	0.5020**	0.2385	1.33+
	Ca^2	-0.1810+	-0.3928**		
	P^2	-0.0042	-0.0494+		
	K^2	-0.1068**	-0.0728*		
	Ca^2	0.0157	0.0505+		
	PK	0.0793**	0.0887**		
	PCa	0.0345+	0.0331		
	KCa	-0.0067	0.0217		
	PKCa	-0.0115+	-0.0139+		
	R^2	0.8768	0.8573		
	Experimental error			0.06683	

Table 87b. (Continued)

Element	Factor	Entry 4 b_i	Entry 5 b_i'	$b_i - b_i'$	$\underline{t}$
Ca(%)	b_o	0.5602**	0.6554**	0.0952	1.68
	P	-0.0210	-0.0081		
	K	-0.0478++	-0.0913**		
	Ca	0.0035	-0.0061		
	P^2	0.0203**	0.0158**		
	K^2	0.0169**	0.0228**		
	Ca^2	0.0108++	0.0122*		
	PK	-0.0181**	-0.0152**		
	PCa	-0.0120*	-0.0106*		
	KCa	-0.0085++	-0.0022		
	PKCa	0.0026+	0.0009		
	R^2	0.7904	0.8274		
	Experimental error			0.00216	
Mg(%)	b_o	0.9841**	1.1438**		
	P	-0.1117+	-0.0435		
	K	-0.0398	-0.1940**	0.1542	1.41+
	Ca	0.1402+	-0.0402	0.1804	1.66+
	P^2	0.0459**	0.0212+		
	K^2	-0.0190	0.0045		
	Ca^2	-0.0224+	0.0073		
	PK	-0.0119	-0.0037		
	PCa	-0.0085	-0.0022		
	KCa	0.0200++	0.0420**		
	PKCa	-0.0050	-0.0061+		
	R^2	0.7596	0.7991		
	Experimental error			0.01404	

Table 87b. (Continued)

Element	Factor	Entry 4 b_i	Entry 5 b_i'	$b_i - b_i'$	t
N(%)	b_o	2.0491**	2.2762**		
	P	-0.4717**	-0.5567**		
	K	-0.1217	-0.1922+		
	Ca	0.0106	-0.1586+		
	P^2	0.0953**	0.1220**		
	K^2	0.0152	0.0224		
	Ca^2	0.0248	0.0527		
	PK	0.0050	0.0025		
	PCa	-0.0332*	-0.0184		
	KCa	0.0086	0.0299+		
	PKCa	-0.0047	-0.0096		
	R^2	0.8600	0.7741		
	Experimental error			0.04549	

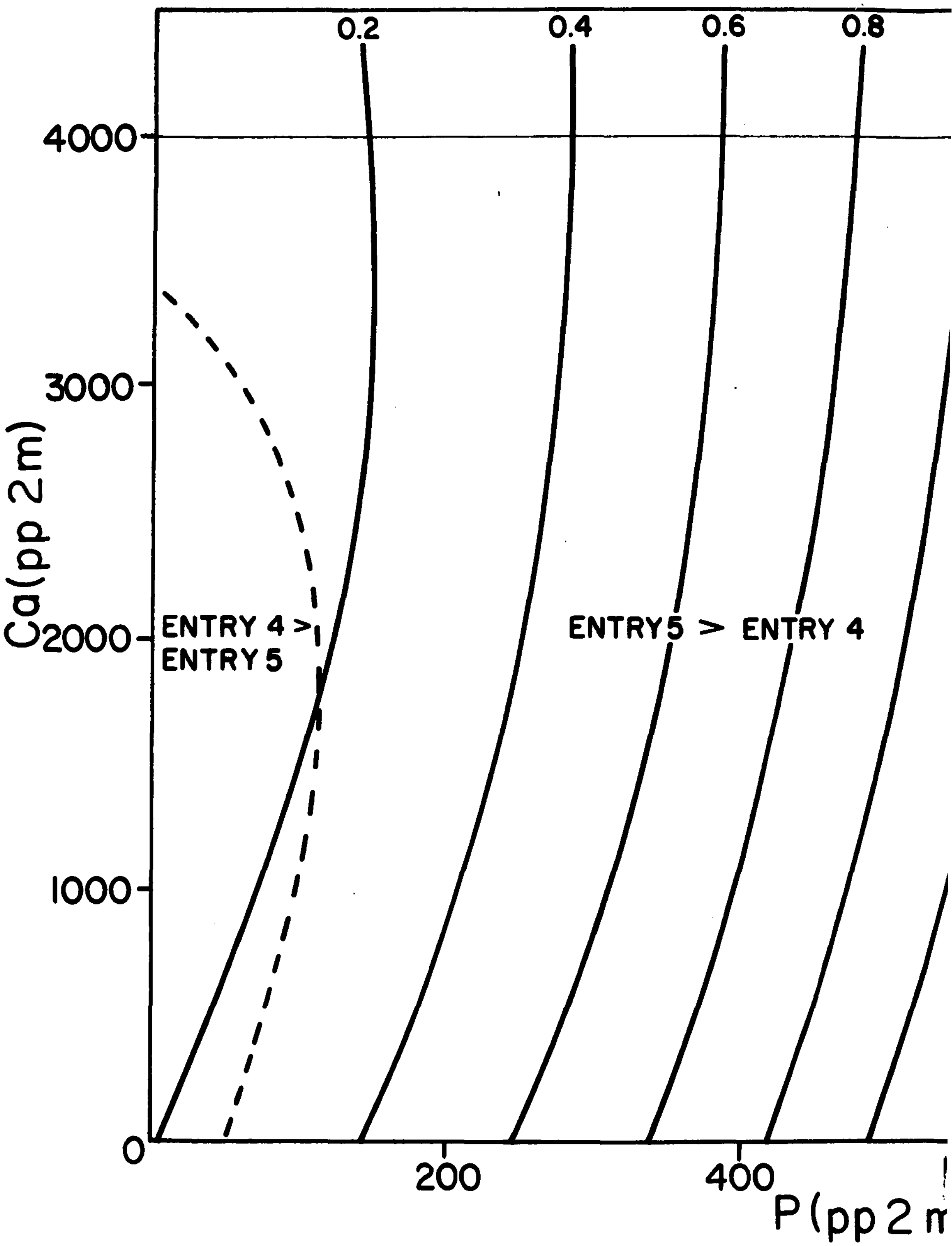
The percent Ca was affected significantly by all three factors although P and Ca were involved by their quadratic components and interaction terms only.

The contour map for the percent Ca in the roots is similar to that for the leaves and shows a minimum at 390 pp2m P and 520 pp2m K when 2000 pp2m Ca were applied (Figure 29).

The percent Mg was influenced by different factors for each of the 2 lines. The K, Ca, P^2 and KCa interaction effects reached a significance level of 0.05 or higher. Figure 30 illustrates the effect of P and K on the percent Mg in the roots. The percent N was mainly affected by the linear and quadratic components of P.

Figure 27. Contours of percent P in the roots at the 4.5-leafed stage for Entry 4, grown in pots in 1962, as a function of P and Ca, holding K constant at 400 pp2m and the projection of the line of intersection between the surfaces for Entries 4 and 5

Contours
Projected line of intersection
Limits of investigated area


0.2
0.4
0.6
0.8
4000
3000
2000
1000
0
Ca(pp 2m)
ENTRY 4 >
ENTRY 5
ENTRY 5 > ENTRY 4
200
400
P (pp 2 m

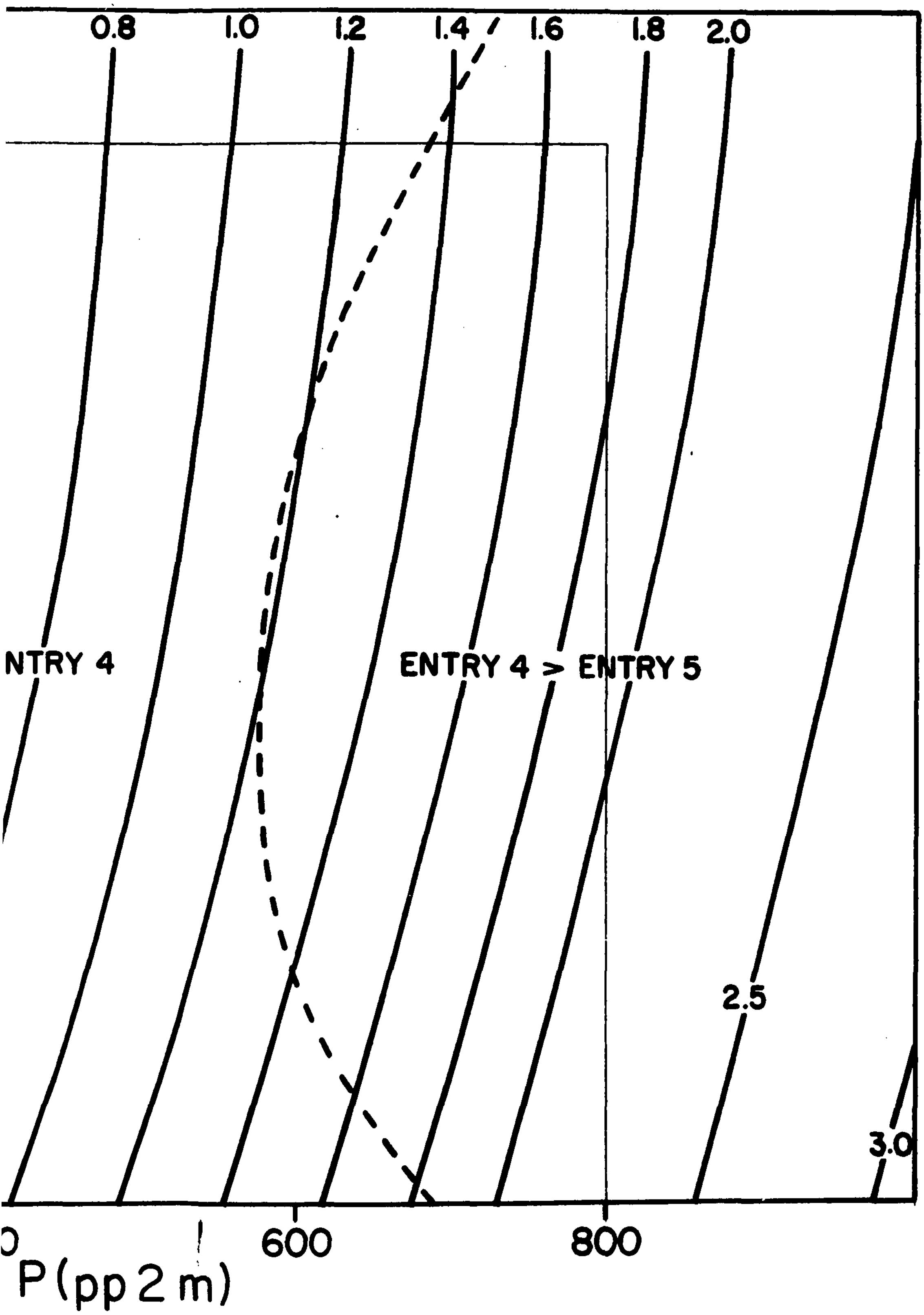
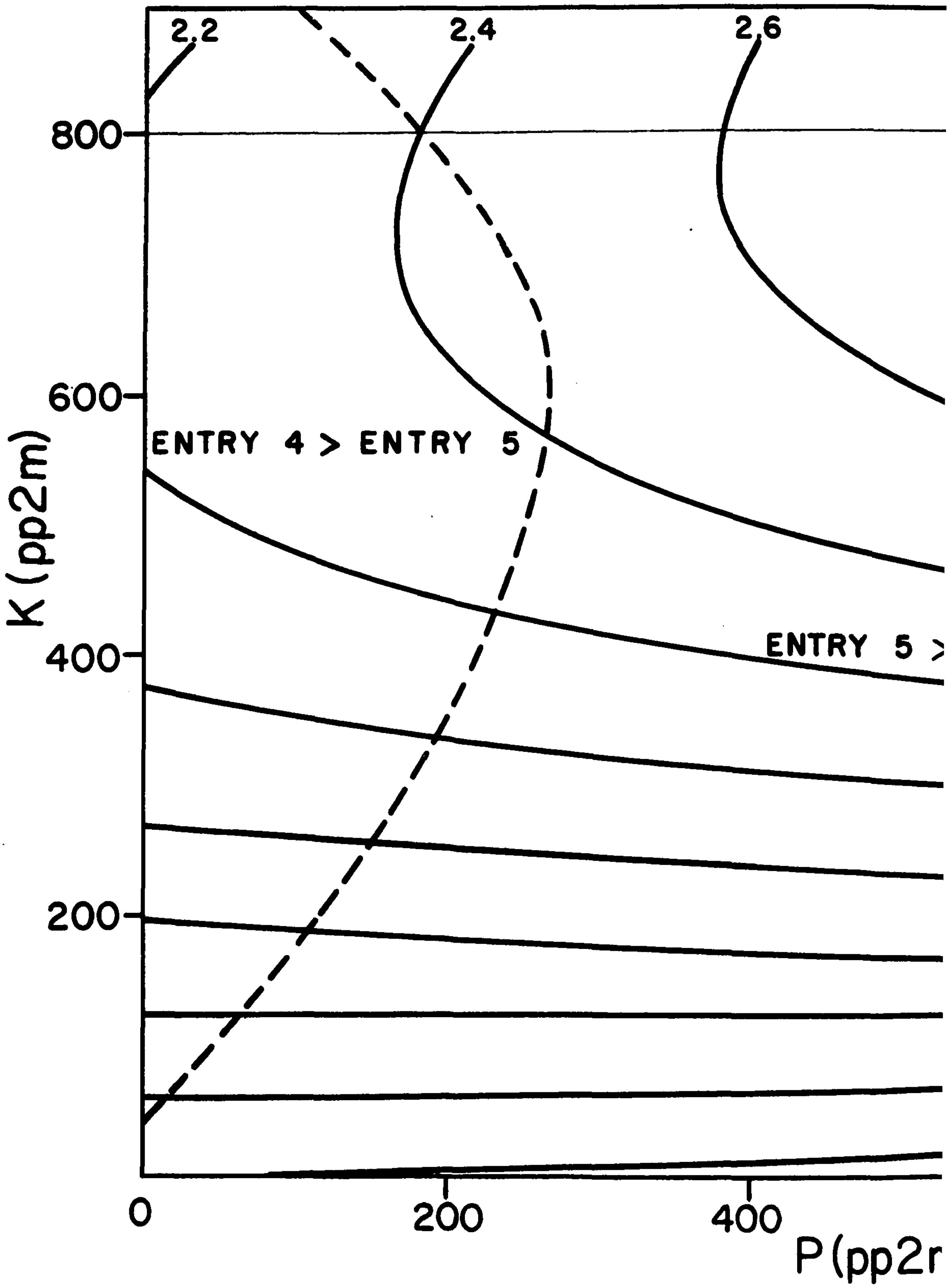
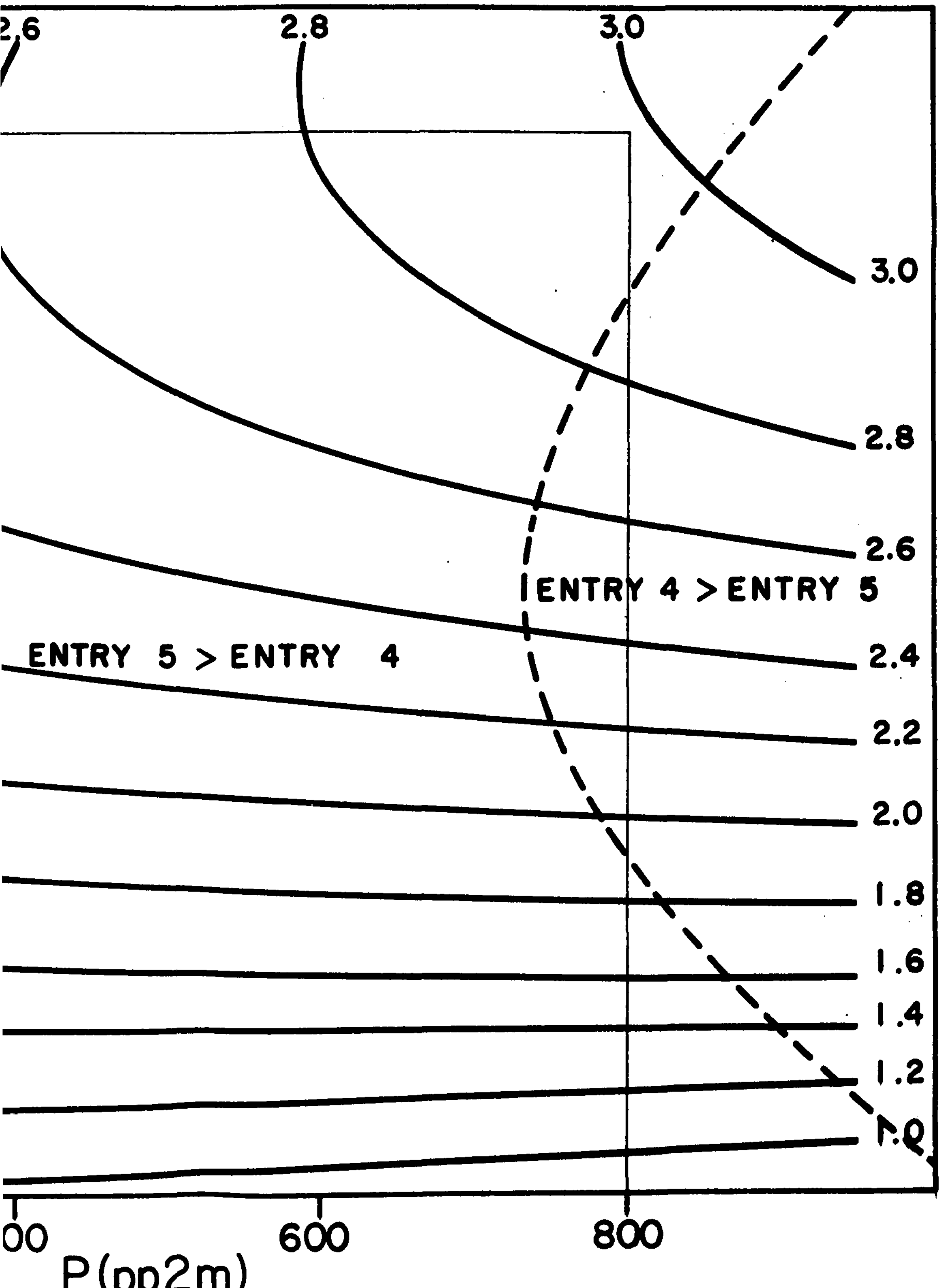

0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.5
3.0
NTRY 4
ENTRY 4 > ENTRY 5
600
800
P (pp 2 m)

Figure 28. Contours of percent K in the roots at the 4.5-leafed stage for Entry 4, grown in pots in 1962, as a function of P and K, holding Ca constant at 2000 pp2m; and the projection of the line of intersection between the surfaces for Entries 4 and 5

——— (heavy line)	Contours
— — — —	Projected line of intersection
——— (light line)	Limits of investigated area



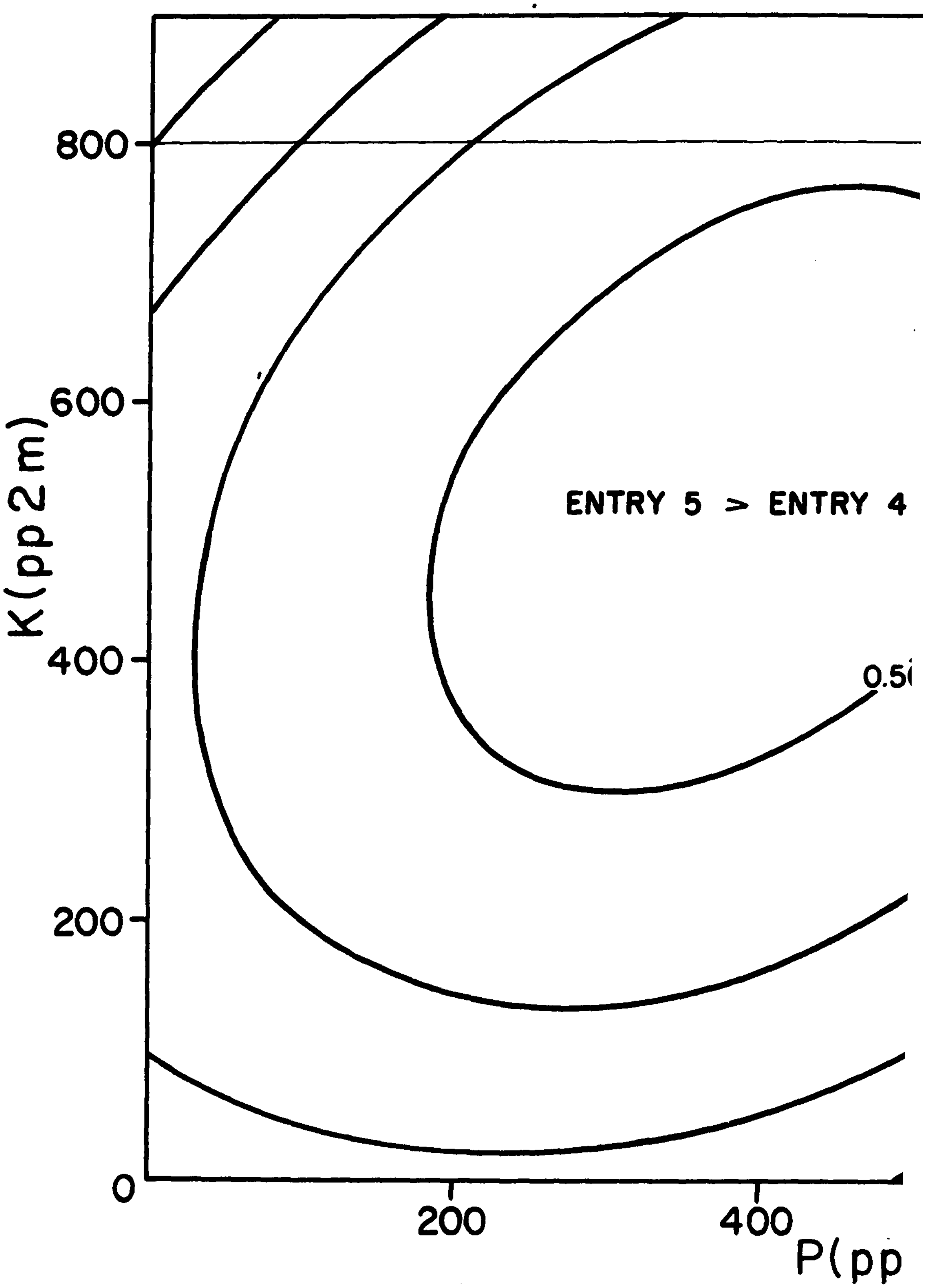
2.2
2.4
2.6
800
600
400
200
K (pp2m)
ENTRY 4 > ENTRY 5
ENTRY 5 >
0
200
400
P (pp2r



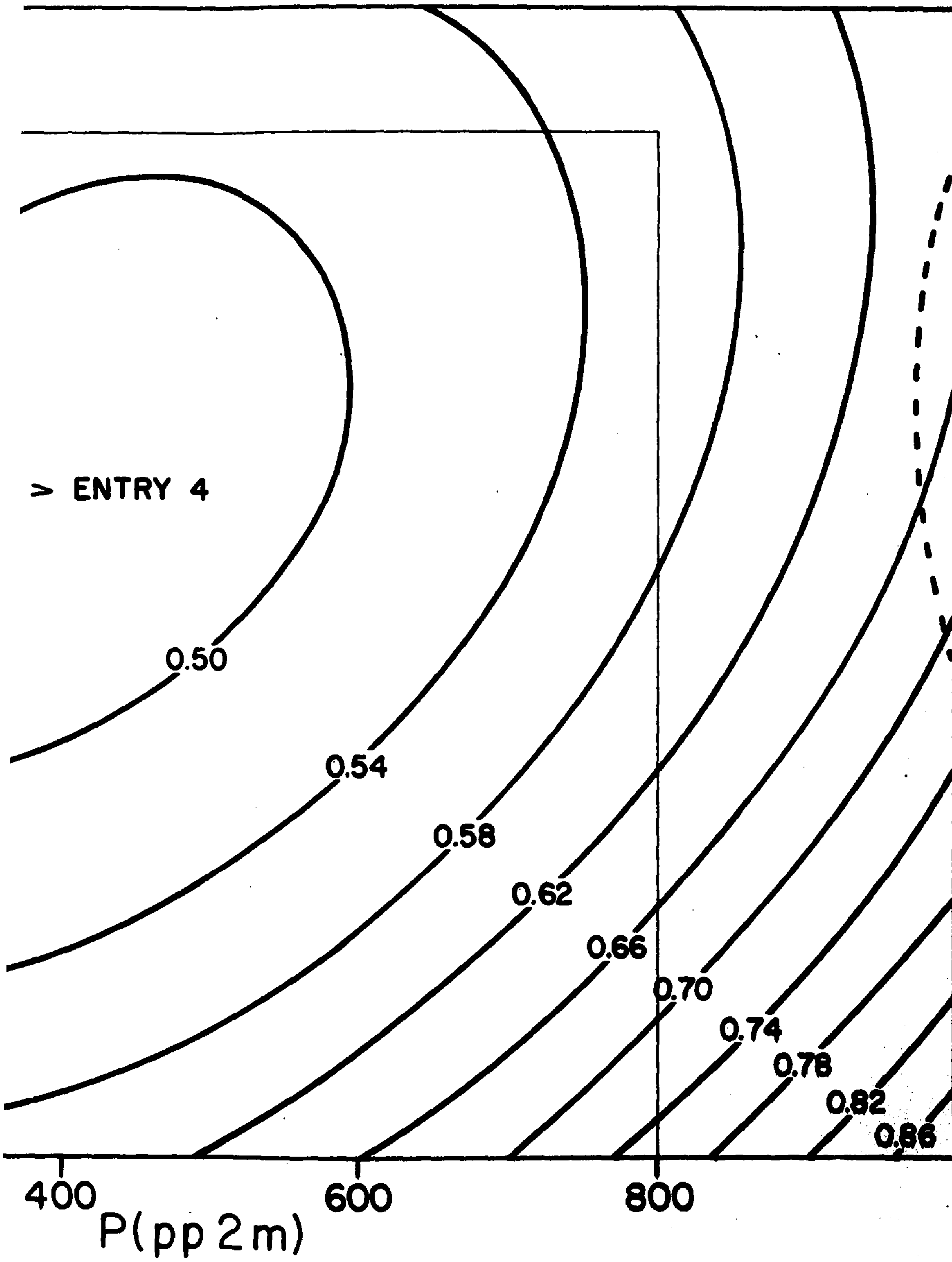
2.6
2.8
3.0
3.0
2.8
2.6
ENTRY 4 > ENTRY 5
2.4
ENTRY 5 > ENTRY 4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
00
600
800
P(pp2m)

Figure 29. Contours of percent Ca in the roots at the 4.5-leafed stage for Entry 4, grown in pots in 1962, as a function of P and K, holding Ca constant at 2000 pp2m; and the projection of the line of intersection between the surfaces for Entries 4 and 5

———	Contours
— — — —	Projected line of intersection
———	Limits of investigated area



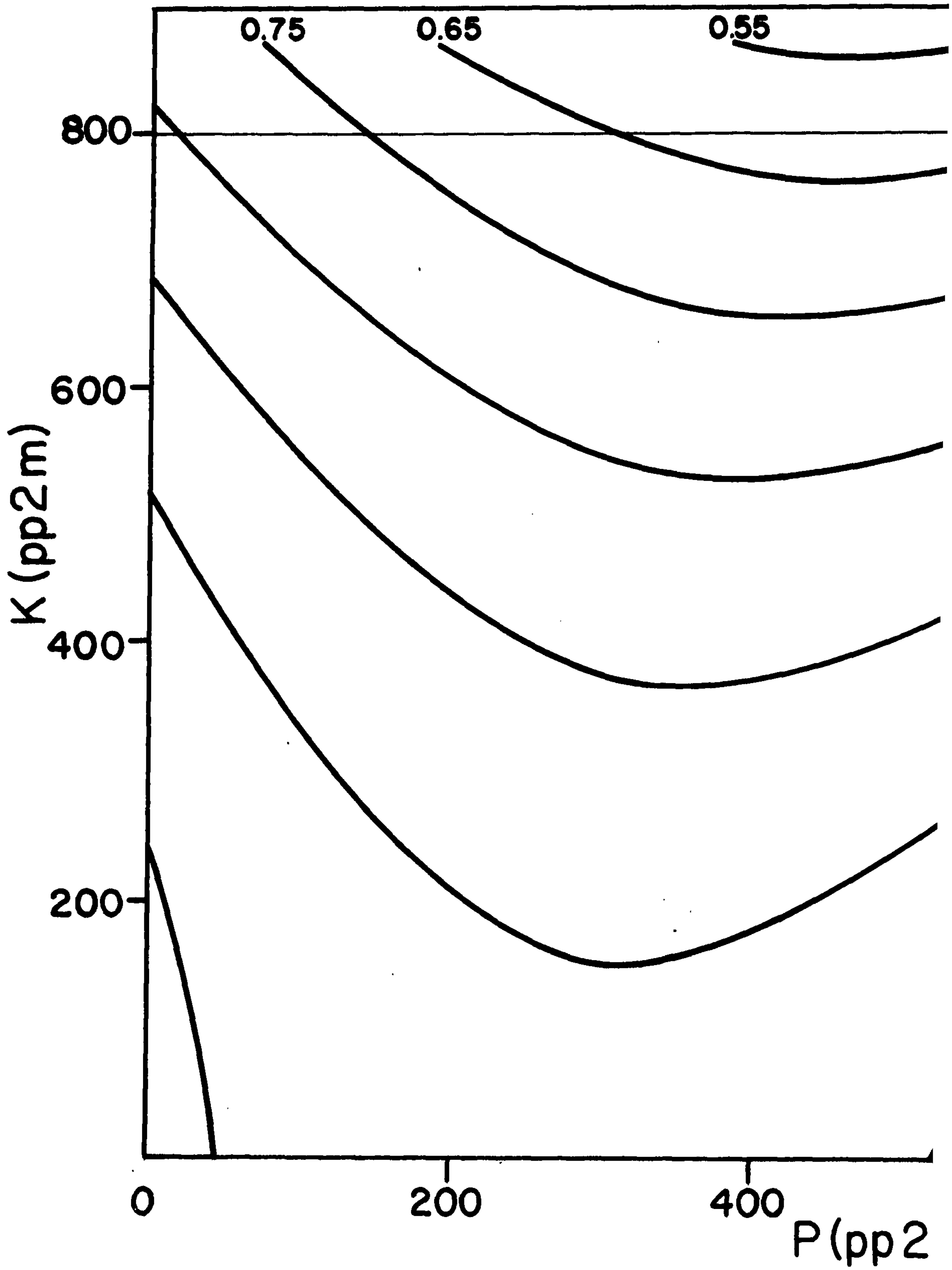
ENTRY 5 > ENTRY 4
0.5
800
600
400
200
0
K(pp2m)
200
400
P(pp

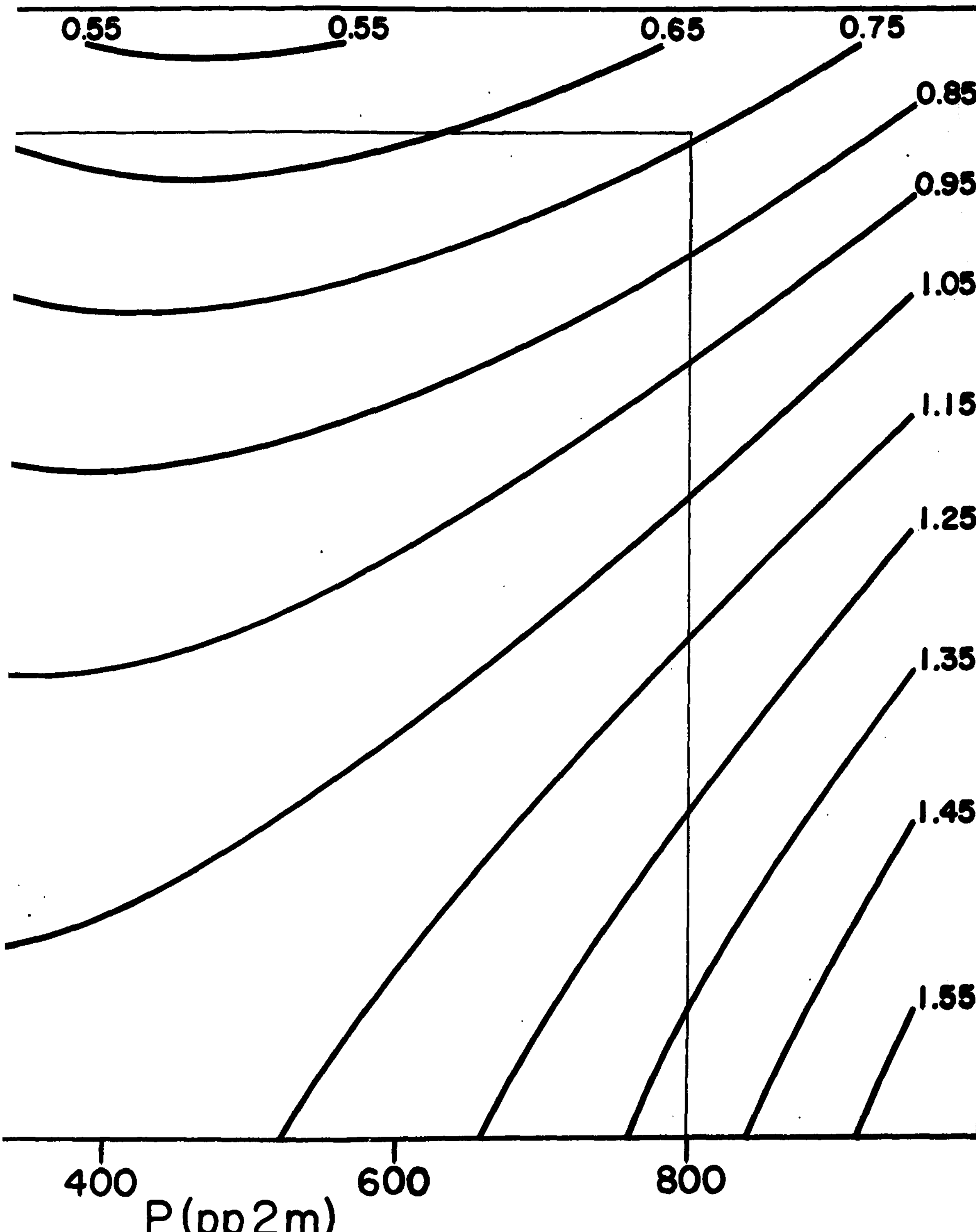


> ENTRY 4
0.50
0.54
0.58
0.62
0.66
0.70
0.74
0.78
0.82
0.86
400
600
800
P(pp 2m)

Figure 30. Contours of percent Mg in the roots at the 4.5-leafed stage for Entry 4, grown in pots in 1962, as a function of P and K, holding Ca constant at 2000 pp2m

——————— Limits of investigated area


0.75
0.65
0.55
800
600
400
200
K (pp2m)
0
200
400
P (pp2


0.55
0.55
0.65
0.75
0.85
0.95
1.05
1.15
1.25
1.35
1.45
1.55
400
600
800
P (pp 2m)

Differential responses in percent P, due to P application reached the 0.01 level of significance. Weaker differential effects occurred in percent K and percent Mg. Those of the percent K were due to the factor K and those for the percent Mg were caused by K and Ca. A varietal difference in the percent Ca of the two lines was indicated at the 0.10 level of significance and this was not influenced by fertilization. No differential responses existed in the percent N of the roots of the 2 lines.

It appears from Figures 22 and 27 that Entry 4 had a higher P content in the plant than Entry 5 at very high rates of P application and also when very light rates were applied. The region over which Entry 5 had a higher P content is larger for roots than for tops. The partitioning of the region of fertilization for the percentages K and Ca according to the variety with higher nutrient content in the roots was very similar to that for the tops (Figures 23, 24, 28 and 29). That for the percent Mg was different (Figures 25 and 30). Entry 4 contained more Mg in the roots over the entire investigated area, while Entry 5 generally had a higher content in the tops.

The magnitude of the responses in nutrient composition of the roots to fertilizer application for both soybean lines was determined by graphical interpretation of contour maps and is summarized in Table 88.

The magnitude of the predicted response in percent P to 300 pp2m P per acre was large. That to 2000 pp2m of Ca was smaller and negative. Those of the percent K in the roots to K and Ca were respectively positive and negative and of the same order as those for the leaves.

Table 88. Magnitude of predicted responses and differential responses of root composition of two soybean lines, grown in pots in 1962 and harvested at the stage of 4.5 trifoliate leaves to applied P, K and Ca involving one or more significant effects

Dependent variable	Entry	Factor specification (pp2m) P	K	Ca	Percentage composition from	to	response	Differential response
%P	4	0-300	400	2000	0.05	0.50	0.45	
	5	0-300	400	2000	0	0.56	0.56	0.11
	4	300	400	0-2000	0.72	0.50	-0.22	
	5	300	400	0-2000	0.85	0.56	-0.29	
%K	4	300	0-400	2000	0.90	2.15	1.25	
	5	300	0-400	2000	1.16	2.20	1.04	0.21
	4	400	400	0-2000	2.50	2.20	-0.30	
	5	400	400	0-2000	2.80	2.25	-0.55	
%Ca	4	0-300	400	2000	0.56	0.49	-0.07	
	5	0-300	400	2000	0.59	0.54	-0.05	
	4	300	0-400	2000	0.60	0.49	-0.11	
	5	300	0-400	2000	0.70	0.49	-0.21	
	4	400	400	0-2000	0.50	0.49	-0.01	
	5	400	400	0-2000	0.55	0.54	-0.01	
%Mg	4	0-300	400	2000	1.10	0.95	-0.15	
	5	0-300	400	2000	0.90	0.83	-0.07	
	4	300	0-400	2000	1.10	0.95	-0.15	
	5	300	0-400	2000	1.08	0.83	-0.25	0.08
%N	4	0-300	400	2000	2.02	1.42	-0.60	
	5	0-300	400	2000	2.00	1.32	-0.58	

The predicted responses of the percent Ca were all negative and small due to the position of the selected range of fertilization in relation to the location of the minimum percent Ca. Similarly the response of the percent Mg to P may be either positive or negative depending on the chosen rates of fertilizer application. The percent N was substantially reduced by P application. The increase in size of root system was not strong enough to compensate for this even on a total N content basis. It appears that while the plant prospered under P application and had a larger N supply, the root system actually contained less N.

The predicted nutrient content over the range from unfertilized conditions to that fertilizer combination leading to maximum content was very wide for the percent P and percent K and rather more narrow for the percent Ca and percent Mg (Table 89). It appears that the maximum percent P in the roots remained well below that of the leaves. This also applied to the percent Ca which was 3 times higher in the leaves and to the percent N which was about twice as high in the leaves as in the roots. The percent K on the other hand was equal in both organs of the plant and the percent Mg was somewhat higher in the roots than in the leaves. These findings applied to both soybean lines.

4. Growth characteristics as a function of chemical composition of leaves and roots

It may be expected reasonably that the yield of soybeans is related to the nutrient composition of the leaves at certain stages of development. Many reports relate the content of one nutrient to yield. Recently

Table 89. Fertilizer combinations required for the maximum percentage content of nutrients in the roots within the investigated region of fertilization and predicted range of nutrient content in the roots of two soybean lines, grown in pots in 1962

Dependent variable	Entry	Fertilizer combination (pp2m)			Range	
		P	K	Ca	check	max.
%P	4	800	0	0	0.14	2.43
	5	800	0	0	0.19	2.23
%K	4	800	800	0	1.32	3.40
	5	800	800	0	1.61	3.60
%Ca	4	800	0	0 or 4000	0.56	0.80
	5	800	0	0 or 4000	0.66	0.88
%Mg	4	800	0	2300	0.98	1.40
	5	800	0	0	1.14	1.32
%N	4	0	0	4000	2.05	2.50
	5	0	800	4000	2.28	2.50

Dumenil (1961) expressed the yield of corn as a function of the N and P contents of corn leaves and Miller et al. (1964) related the yield of soybeans to the P and K contents of leaves or petioles determined at various stages of development. Dumenil reported equations which were satisfactory for determination of critical nutrient levels. A highly significant correlation existed between the percent N and percent P, but it was decided that the interpretation was not seriously affected.

Some difficulties exist with similar relationships for soybeans. Miller et al. reported a rather variable distribution of significant terms in the fitted equations over various experiments and plant parts chosen for nutrient determination. Many factors may have contributed to this situation and one of them is that the nutrient composition of some plant parts may hold better relationships with grain production than others. In an earlier section the yield of grain or dry-matter production was expressed as a function of the composition of the leaves with respect to P, K, Ca, Mg and N with doubtful results. In the present experiment the relationships between the chemical composition of certain plant parts and production of dry matter were expressed in multiple regression equations in several ways. The chemical composition of leaves and roots with respect to the nutrients P, K, Ca, Mg and N was expressed on a dry weight percentage, a total content and a fresh weight percentage basis. Deviations of these values from their mean as well as their squares and first-order interactions were calculated. Sets of these values of the chemical composition of leaves and roots, for each of the 2 lines of soybeans and in each mode of expression were used as independent variables in separate multiple regression equations. The dry weights of tops, roots and leaves served in turn as dependent variables. Significant *t*-values on the partial regression coefficients so obtained are given in Table 90. Considering each equation separately, many of them could be accepted on the basis of a logical explanation for several terms reaching significance and on the total variation explained. On the basis of high multiple R^2 values alone every equation was satisfactory. In each case between 81 and 98% of the variation in the dependent variable was explained by the 20 independent variables excluding the intercept. Equations employing

Table 90. Values of _t_ for partial regression coefficients reaching the 0.20 level of significance or higher in equations relating dry-matter production of tops, leaves and roots of two soybean lines, grown in pots in 1962 and harvested at the stage of 4.5 trifoliate leaves to leaf or root composition expressed in one of three ways: dry-weight percentages, fresh-weight percentages or total contents of five nutrient elements; and values of R^2

Independent variables and R^2	Dry weight of tops as dependent variable					
	Leaf composition as independent variables					
	Dry weight %		Total content		Fresh weight %	
	Entry 4	Entry 5	Entry 4	Entry 5	Entry 4	Entry 5
b_o	19.47**	10.64**	31.17**	24.64**	14.08**	10.44**
P					1.80++	2.09*
K	1.65+		4.39**	2.00++	2.02++	
Ca			1.78++	4.09**		1.50+
Mg				1.94++	1.46+	
N		1.70+				
P^2	1.92++		1.45+	1.55+	3.67**	
K^2	1.70+					
Ca^2				2.27*		
Mg^2	1.84++					
N^2						
PK	2.18*			1.75++		1.87++
PCa				2.24*		
PMg	2.59*			2.58*		2.07*
PN		1.46+			3.56**	1.78++
KCa		1.63+				
KMg	2.01					
KN						
CaMg				1.40+		
CaN				2.11*		
MgN				2.23*		
R^2	0.8687	0.8504	0.9540	0.9654	0.8301	0.8726

Table 90. (Continued)

Independent variables and R^2	Dry weight of tops as dependent variable			
	Root composition as independent variables			
	Dry weight %		Total content	
	Entry 5	Entry 5	Entry 4	Entry 5
b_o	12.03*	15.89**	16.25**	21.23**
P			1.39+	3.22**
K	1.55+			
Ca	1.41+			
Mg		1.66+		1.53+
N	1.52+	2.60*		
P^2	1.76++		2.55*	
K^2				
Ca^2	1.44+	1.72++		
Mg^2	1.62+			
N^2				
PK				
PCa				
PMg				1.72++
PN				
KCa				
KMg				
KN				
CaMg				
CaN				
MgN				
R^2	0.8738	0.8461	0.8761	0.9064

Table 90. (Continued)

Independent variables and R^2	Dry weight of leaves as dependent variable					
	Leaf composition as independent variables					
	Dry weight %		Total content		Fresh weight %	
	Entry 4	Entry 5	Entry 4	Entry 5	Entry 4	Entry 5
b_o	22.28**	9.96**	43.63**	27.86**	14.90**	12.65**
P			1.76++		1.74++	2.08*
K	2.34*		5.65**	2.16*	2.06*	
Ca			2.83**	4.62**		2.29*
Mg	2.14*		1.70+	2.10*	1.62+	1.50+
N		1.95++		1.66+		
P^2	1.61+		1.39+	2.55*	3.78**	
K^2	2.43*					1.37+
Ca^2				1.81++		
Mg^2	2.62*				1.35+	
N^2						
PK	2.94**			3.02**		3.31**
PCa				2.99**		1.55+
PMg	3.67**			3.56**		3.20**
PN		1.35+			3.62**	2.25*
KCa					1.42+	
KMg	2.83**			1.72++		1.58+
KN						
CaMg						
CaN				2.65*		
MgN				2.08*		
R^2	0.8929	0.8168	0.9757	0.9708	0.8352	0.9044

Table 90. (Continued)

Independent variables and R^2	Dry weight of roots as dependent variable			
	Root composition as independent variables			
	Dry weight %		Total content	
	Entry 4	Entry 5	Entry 4	Entry 5
b_o	16.77**	16.29**	31.47**	22.18**
P	1.99++			1.93++
K			2.10*	
Ca	1.51+		2.10*	
Mg			1.33+	
N	2.62*	2.73*	1.89++	1.48+
P^2	1.91++			
K^2			2.06*	
Ca^2	1.38+	1.69+		
Mg^2				
N^2	1.76++			
PK	1.90++	1.72++		
PCa				
PMg		1.58+		
PN	2.08*			
KCa				
KMg	1.48+			
KN	1.40+			
CaMg	2.03++			
CaN				
MgN		1.52+		
R^2	0.9137	0.8465	0.9609	0.9141

total content of nutrients as independent variables had multiple R^2 values larger than 0.95 when the dry weight of tops or leaves was expressed as a function of leaf composition, or when the dry weight of the roots was expressed as a function of root composition. As indicated before the reason for this effect may be the correlation between, for example, leaf weight as dependent variable and total nutrient content because each value of the latter was the product of a percentage content and associated leaf weight. Accordingly, the multiple R^2 values decreased to the level observed when percentage contents are employed as independent variables when the dry-matter production of tops was instead related to total root composition. Presumably, there will be little reason for preference of any other than dry-weight percentage contents as independent variables for most purposes.

Inspection of the equations simultaneously, however, shows the illogical distribution of significant terms. Few corresponding coefficients reached significance. When the dry and fresh weight percentage composition of the leaves are compared as a set of independent variables for either variety (for example, with dry weight of tops as the dependent variable) the two resulting equations may be expected to be rather similar since it was shown in previous sections that little difference existed in the distribution or level of significance of terms affecting the dry- and fresh-weight percentage composition as a function of fertilizer input variables.

As can be seen from Table 90 this did not hold at all. It is further unreasonable that the majority of significant terms did not correspond between varieties regardless which basis of expression of independent variables was selected. The same criticism applies to the case of the other dependent variables.

On the other hand the $\underline{t}$-values and multiple R^2 values were consistently similar in significance and size when the same set of input data was used as independent variables to fit two different dependent variables. For example, when the dry-weight percentages for leaf composition of Entry 4 was used to fit the dry weights of plant tops and dry weight of leaves in turn, the distribution of significant terms was very comparable. This would suggest that no interference was caused by gross errors in the sets of data for the dependent variables, but rather by small differences in the values of different sets of independent variables when expressed in different ways.

Presumably the equations reflecting the production of dry-matter as a function of composition in their present form are not meaningful. Tests on differential effects were not performed since the meaning of any positive results should be doubted similarly.

A possible explanation for interference with logical relationships is a high degree of interdependence among the independent variables. Application of P fertilizer had considerable influence on the percent K and percent N in the leaves as well as on the percent P as was shown in previous sections. K application affected the percent Ca and percent Mg as well as the percent K. These facts are also indicated by the simple correlations between input variables, many of which reach significance (Table 91). The value of r which is significant at the 0.05 level of significance and 44 degrees of freedom is 0.304. This interdependence of the nutrient contents in the leaves may be expected to be stronger in the case of soybeans and legumes in general than for corn, because of the relationships between P fertilization and N fixation discussed.

Table 91. Correlation coefficients between sets of leaf-composition values used as independent variables in multiple regression equations[a]

Mode of expression	Independent variables	Independent variables							
		P	K	Ca	Mg	Ca^2	Mg^2	CaMg	CaN
Dry weight percentage	K	0.2245							
	Ca	0.4141	-0.4229						
	Mg	0.4575	-0.6121	0.6309					
	N	-0.0158	-0.4075	0.2928	0.3197				
	Mg^2	0.5494	-0.3161	0.5404	0.7698	0.3561			
	N^2	-0.0653	-0.3366	0.0658	0.1075	-0.0621	0.0896		
	CaN	0.2046	-0.1433	0.1016	0.1622	0.2659	0.3492	0.3867	
	MgN	0.4268	-0.1677	0.2220	0.5227	0.2294	0.6324	0.5388	0.5434
Total content	K	0.4216							
	Ca	0.4885	0.5883						
	Mg	0.4502	0.1698	0.8131					
	N	0.2566	0.4583	0.7599	0.7154				
	Mg^2	0.1300	-0.2804	0.3320	0.6365	0.7503			
	N^2	0.0394	-0.0074	0.3686	0.5496	0.6483	0.8226		
	CaN	-0.0175	-0.2880	0.1317	0.3920	0.8945	0.8943	0.9433	
	MgN	0.0328	-0.2025	0.2955	0.5747	0.7709	0.9504	0.9443	0.9390

[a]Tabular $r_{(0,05)}$ at 44 degrees of freedom is 0.304.

Sutton (1962), in a discussion of nutrient relationships in corn, concluded that relatively high correlation among independent variables may lead to partial regression coefficients having irrational signs and refers to work by other researchers who arrived at a similar conclusion.

It may be necessary to enter terms which are more nearly independent of other variables and if possible, closer to actual cause and effect relationships than the present ones. For example, evaluation of the K supply of the plant by the percentage or total K content of the petioles or pulvini while other nutrients are determined from the leaves. Another hypothetical term would be the amount of K translocated from the leaves to the growing beans over a short period at a critical stage of development. Moreover, other factors of an environmental nature may be needed to improve the model as linear terms or as interactions with others. Such a situation may be realized from the findings of Howell and Cartter (1958), who reported that the oil content of soybeans can be influenced by raising the day-temperature from 70^{o} to 85^{o} for one week. The oil content rose by 2 1/2 % only when this condition prevailed between 4 and 7 weeks before maturity, which was the period of maximum intensity of oil synthesis. Although it is unlikely that relationships like the above will be discovered by multiple regression studies, the case illustrates the nature of equations which may be required to derive logical relationships between leaf composition and yield of soybeans.

5. Conclusions

It appeared from the symptoms discussed in the first section of this chapter that pots treated with high rates of P, K and Ca received the largest nodule-stimulation from P at the least foliar damage. Withholding any of the three elements resulted in less desirable effects. It would seem that a considerable and meaningful PKCa interaction could be expected. Such a conclusion would not be justified because of the alternative explanation that some of the K and/or Ca at this rate of P application was merely required to reduce the P uptake to a less toxic level. If it were represented in the composite design, some other treatment combination receiving a lower rate of P, might have produced as high or better and develop no P toxicity symptoms at all.

Subsequent regression analysis showed that the P, P^2 and in case of Entry 4 also, the PCa effects had a major influence on the dry weight of tops and roots and were highly significant. The P and P^2 effects had a similarly significant influence on the number and weight of nodules. The response of top growth and nodule weight and number to 300 pp2m P were very large. They were of the order of 100% for the tops and several-fold increases were obtained for nodulation characteristics. The PKCa effect was immaterial. It appeared that the maximum amount of green matter was produced at approximately 525 pp2m P, 725 pp2m K and 3500 pp2m Ca. This almost coincides with the rate of P for maximum number of nodules which was estimated at 550 pp2m P. In fact, most characteristics reached a maximum at a rate of P application between 500 and 590 pp2m with the exception of the dry-weight of the roots for Entry 4 and the fresh weight of nodules for Entry 5. These required somewhat lower rates of P. The maximum response of the number of nodules to any combination of fertilizers was 22-fold and that of nodule weight 10-fold. It may be assumed that the top growth benefited from the associated increase in nitrogen fixation and supply. This resulted in a 2.3-fold increase in weight of tops. The stems were visibly thicker, showed marks of dilatation and received the largest benefit (2.7-fold increase). The petioles responded 2.6-fold and the leaves 2.1-fold. The leaves are also the farthest removed from the source of supply and are placed outside the mainstream of nutrients to vegetation points which could be more than coincidence.

The P^2 and PCa interaction effects caused differential responses with respect to top growth between the two lines which were significant at the 0.05 and 0.10 level for these effects respectively. The same factors also provoked a different response in nodulation of the two lines. The significance level of 0.20 was low. It is thought, however, that these differences were meaningful and that the variance can be considerably reduced by more accurate measurements. Once differential effects have been established with high probability of significance, their magnitude determines the practical importance of the findings. This depends on the interplay of two full sets of partial regression coefficients and on the chosen values of the independent variables for response measurement. Such responses, when evaluated by pair-wise interpretation of isoquant maps, indicated a 100% increase in dry weight production of plant tops to application of 300 pp2m P and a differential response of the order of 30%.

The leaf composition was strongly affected by fertilization. P application resulted in highly significant changes in the percent P in the leaves. The P content covered a range from 0.1% to over 4.0%. Application of P also affected the percentages K, Mg and N to the 0.05 level of significance and higher. Similarly, K application not only resulted in a wide range of percent K, but also affected the percentages Ca, Mg and N. Ca application influenced the percentages P and K significantly as well as the percent Ca. It can therefore be seen that by any change in leaf composition caused by a variation in supply of P, K and Ca in the soil the change in content of several nutrients will be correlated to a certain extent. When such interrelated leaf composition values were employed as independent variables in multiple regression equations an inconsistent distribution of significant partial regression coefficients resulted. This rendered the equation unsuitable for the purpose of computing critical nutrient values. Critical values were therefore obtained from a number of multiple regressions all of which were based on fertilizer input as independent variables and having as dependent variables the yield of dry-matter produced and the contents of each nutrient respectively. After the fertilizer combination corresponding to maximum yield of dry matter had been determined by graphical means, substitution of these values into each of the equations having the percentage nutrient as the dependent variable rendered a set of critical values for each line of soybeans. The critical values the percent P and percent K may have been higher than they would have been under field conditions.

The chemical composition of the roots was similarly affected by fertilizers to that of the leaves. A wide range of percent P and percent K was created in response to P and K fertilizers and it may be concluded that under the conditions of the experiment the chemical composition of both plant parts responded strongly to fertilization. The percentages of P, K, Ca and Mg of either, leaves or roots, or both showed significant differential effects due to P or K application between the two soybean lines.

A comparison of the results of fitting the same model to dry weight and fresh weight data for several plant parts indicated no advantage for the use of fresh weight data. A similar comparison for nutrient contents expressed on a dry-weight percentage, total content and fresh-weight percentage basis in general indicated that no higher proportion of the variation in chemical composition data could be explained by expressing the results other than as dry-weight percentage values. Dry- and fresh-weight percentages were equally satisfactory as dependent variable on the basis of logical distribution of significant partial regression coefficients, while total contents were generally less satisfactory with the exception of perhaps total K contents under certain conditions.

The experiment established that soybeans respond very strongly to fertilization in terms of dry-matter production as well as uptake of nutrients. A wide range of contents of the major nutrients can be induced by fertilization. Important relationships between P fertilization, nodulation, growth and P toxicity were found and analyzed quantitatively. The question remains, however, whether such responses at a young stage of development will be further accentuated at later stages and whether they result in large differences in yield of soybeans, or gradually disappear with further development. It was therefore desirable to carry a similar experiment to maturity and to measure responses at certain times during the season. The results of such an experiment are discussed in the next section.

B. Pot Experiment 1963; Results and Discussion

1. Leaf symptoms in relation to chemical composition of the leaves

The symptoms observed in 1963 with different soybean lines (Entries 1, 2 and 3) were identical, to those described in the previous trial. The symptom development was less severe because the rates of P application had been reduced by a factor 0.75. It is evident from Plates 13 and 14 that at the seven-leafed stage treatment 19 which received a high rate of P was most affected, followed by treatment 20, consisting of high P and Ca. All lines receiving this treatment were moderately affected while treatment 22 which received all three elements, showed only discoloration of some lower leaves and this in case of Entry 3 only. All plants fertilized with P were taller at the seven-leafed stage than those of any other treatment (Plate 15). Differential development of P toxicity symptoms was clearly visible. Plates 13 and 16 show that Entry 3 was more seriously affected than Entry 1 under treatment 19 and 21 while Entry 2 was intermediate between the two. The large differences in growth were maintained and increased with further development. The high P, K and Ca treatment of Entry 3 is shown in comparison to the check at the end of flowering (Plate 17).

Plate 13. Pot experiment 1963; from left to right: Entries 1, 2 and 3 receiving a high rate of P, at the seven-leafed stage of development

Plate 14. Pot experiment 1963; from left to right: Entry 3 receiving high rates of P and Ca, P and K and P, K and Ca, at the seven-leafed stage of development

Plate 15. Pot experiment 1963; from left to right: Entry 1 receiving no fertilizer, high rates of K and Ca, and P, at the seven-leafed stage of development

Plate 16. Pot experiment 1963; from left to right: Entries 1, 2 and 3 receiving high rates of P and K, at the seven-leafed stage of development

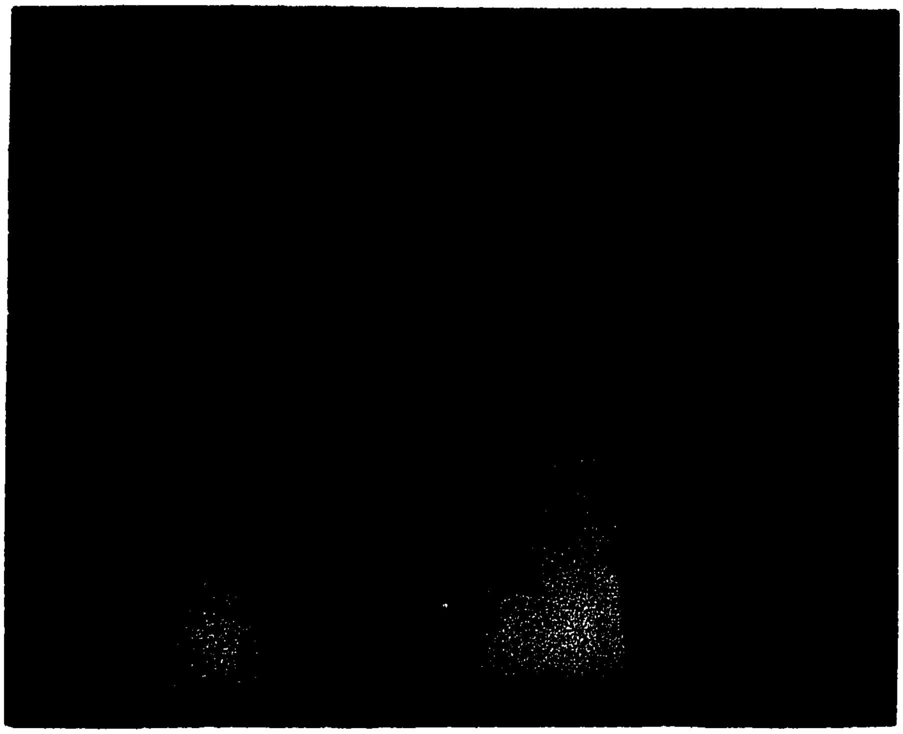


Plate 17. Pot experiment 1963; Entry 3 at the end of flowering, receiving high rates of P, K and Ca at left and no fertilizer at right

Plants affected by P toxicity tended to grow out of this condition at later stages. There was no recovery of leaves once they were discolored, but newly formed growth was less severely affected as time progressed through the season and depending on the treatment imposed. Discolored leaves were shed up to the seventh or ninth trifoliate leaf as new ones appeared. The degree of symptom development was assessed visually and denoted by a value in the range from 0 to 5. Checking this symptom assessment versus the P content of the leaves in Table 92 at the two-leafed stage a content larger than 1% correlated well with the occurrence of symptoms for Entry 1, 0.90% for Entry 2 and 0.85% for Entry 3. Since no leaf symptoms occurred at the time of sampling the leaf composition data for the seven-leafed stage were also recorded in Table 92 and it can be seen that the percent P changed very little over this period. Yellowing of the cotyledons had been evident since the tenth day after emergence. Leaf symptoms appeared almost overnight during unfolding of the third trifoliate leaf.

It was found that Entry 3 was affected by P toxicity under treatments 11 and 22 whereas Entry 1 remained healthy. Entry 3 therefore is a more sensitive variety. It would be expected then from the findings of Foote and Howell (1964) that Entry 3 would accumulate more P than Entry 1 under the same treatment.

Foote and Howell grew soybean seedlings with expanding unifoliate leaves in nutrient cultures containing from 0.32 to 32 millimoles P per liter for three to four days. They reported that Chief, a P-tolerant variety, developed symptoms at 16 millimoles, whereas Lincoln, a P-

Table 92. Leaf-symptom development at the three-leafed stage in relation to the chemical composition of the leaves at two stages of growth for three soybean lines grown in pots in 1963

Entry	Growth stage	Rate of fertilization (pp2m)			Treatment number	Symptoms[a]	%P	%K	%N
		P	K	Ca					
1	two-leafed	600	400	2000	11	0	0.93	3.22	4.86
		0	0	4000	16	0	0.20	1.67	4.98
		0	800	0	17	0	0.21	2.54	4.63
		0	800	4000	18	0	0.20	2.62	4.59
		600	0	0	19	4	1.50	2.21	5.33
		600	0	4000	20	2	1.12	1.68	5.29
		600	800	0	21	3	1.30	3.86	5.40
		600	800	4000	22	0	0.94	3.41	5.39
		0	0	0	23	0	0.23	1.91	4.89
	seven-leafed	600	400	2000	11	0	0.95	2.76	4.56
		0	0	4000	16	0	0.30	1.70	4.19
		0	800	0	17	0	0.23	2.38	3.92
		0	800	4000	18	0	0.25	2.37	3.57
		600	0	0	19	4	1.57	1.87	4.60
		600	0	4000	20	2	1.35	1.37	4.34
		600	800	0	21	3	1.49	3.31	4.38
		600	800	4000	22	0	0.90	2.73	4.73
		0	0	0	23	0	0.25	1.97	3.88

[a]Relative degree of leaf-symptom development for the experiment

Table 92. (Continued)

Entry	Growth stage	Rate of fertilization (pp2m)			Treatment number	Symptoms[a]	%P	%K	%N
		P	K	Ca					
2	two-leafed	600	400	2000	11	0	0.92	2.81	5.08
		0	0	4000	16	0	0.18	1.52	4.90
		0	800	0	17	0	0.19	2.50	4.81
		0	800	4000	18	0	0.18	2.44	4.68
		600	0	0	19	4	1.50	2.26	5.41
		600	0	4000	20	2	1.12	1.94	5.15
		600	800	0	21	3	1.42	3.58	5.46
		600	800	4000	22	1	0.97	3.03	5.19
		0	0	0	23	0	0.22	1.87	4.94
	seven-leafed	600	400	2000	11	0	1.25	2.53	4.05
		0	0	4000	16	0	0.26	1.87	3.78
		0	800	0	17	0	0.27	2.53	4.19
		0	800	4000	18	0	0.21	2.29	3.79
		600	0	0	19	4	1.90	2.10	4.16
		600	0	4000	20	2	1.13	1.55	3.83
		600	800	0	21	3	1.54	2.79	4.10
		600	800	4000	22	1	0.89	2.33	3.86
		0	0	0	23	0	0.24	1.97	3.49

Table 92. (Continued)

Entry	Growth stage	Rate of fertilization (pp2m) P	K	Ca	Treatment number	Symptoms[a]	%P	%K	%N
3	two-leafed	600	400	2000	11	1	0.85	3.24	4.73
		0	0	4000	16	0	0.16	1.48	4.57
		0	800	0	17	0	0.19	2.76	4.53
		0	800	4000	18	0	0.17	2.68	4.66
		600	0	0	19	5	1.65	2.32	5.31
		600	0	4000	20	3	1.06	1.92	5.14
		600	800	0	21	4	1.51	4.16	5.22
		600	800	4000	22	1	0.86	3.70	5.13
		0	0	0	23	0	0.22	2.06	4.80
	seven-leafed	600	400	2000	11	1	1.07	2.73	4.60
		0	0	4000	16	0	0.24	1.72	3.54
		0	800	0	17	0	0.21	2.54	3.66
		0	800	4000	18	0	0.21	2.38	3.82
		600	0	0	19	5	1.98	2.12	4.30
		600	0	4000	20	3	1.44	1.50	4.49
		600	800	0	21	4	1.55	2.94	4.59
		600	800	4000	22	1	0.90	2.91	4.47
		0	0	0	23	0	0.23	1.96	3.73

sensitive variety was already affected at 1.6 millimoles P per liter of solution. When symptoms appeared the P content in the cotyledons of both varieties was about 1.2%.

In the present experiment a number of cotyledons were collected five days after the first signs of yellowing from all pots receiving a high rate of P only. At this time the first trifoliate leaf was formed. The P content of this collective sample was 1.2%. That of healthy cotyledons from unfertilized pots was 0.28%. Contrary to expectation it appeared, however, that at the two-leafed stage the percent P in the leaves of Entry 3 was lower than that for Entry 1 for all original analytical values concerning treatments 11 and 22. The difference between the values for treatment 22 was tested by setting a confidence interval on the predicted values (Fuller, 1962). The formula used was

$$\text{C.I.} = \hat{Y} \pm t_{\alpha} s \sqrt{1 + \frac{1}{n} + X'S^{-1}X},$$

where s is the standard error based on deviations from regression. The $\hat{Y}$ value for treatment 22 of Entry 1 was 0.89% and for Entry 3 it was 0.84%. The confidence interval on the first value at the 0.05 level of probability was found to be 0.89 $\pm$ 0.18, which indicated that the difference was not significant. The conclusion of this experiment therefore was not different from that arrived at by Foote and Howell.

The possibility of causes other than P toxicity for the symptoms observed had to be investigated. Induced K, Zn and Fe deficiency were among the possible alternatives. The K content in the plant was not involved as a causal effect since symptoms occurred at K levels below that of the healthy check pots as well as at double that percentage (Table 92). The N content of the leaves was correlated to some extent with the P contents and therefore also with the occurrence of symptoms. This would be expected from the strong beneficial effect of P application on nodulation which was demonstrated in the previous trial and which also occurred here. By the end of flowering the percentage content of P, K and N had fallen considerably (Table 93). The P content was now lower than 1.0% in all cases except treatment 19. This agrees with the observation that new growth later in the season tends to be more healthy. It also suggests two mechanisms whereby the plant will recover from P toxicity in the field:

1. dilution of the amount absorbed by new growth and abscission of affected leaves, and
2. root systems of plants growing in the field may expand into non-fertilized subsoil horizons.

More detailed information could presumably have been obtained if upper and lower leaves had been separated. Ohlrogge (1960) quoted work by Mederski who found, as early as 1950, that the growth of soybean plants grown in sand culture was depressed by high rates of P. 40 days after planting the upper leaves contained 0.74% and the lower leaves 1.06%P. It was concluded that the lower leaves acted as storage organs. Disposal organs might have been a more appropriate term.

It is unlikely that either deficiency or toxicity of any other

Table 93. Leaf-symptom development at the three-leafed stage in relation to chemical compos

Coded rate of fertilization P	K	Ca	Treatment number	Symptoms[a] at early stages	%P	%K	%N	%Ca	%Mg
0	0	4000	16	0	0.18	1.29	3.24	1.66	0.48
0	800	0	17	0	0.16	2.33	3.14	1.38	0.56
0	800	4000	18	0	0.19	2.15	3.45	1.52	0.38
600	0	0	19	4	1.15	1.19	4.93	1.93	0.60
600	0	4000	20	2	0.84	0.79	4.25	2.14	0.71
600	800	0	21	3	0.89	2.72	4.89	1.37	0.37
600	800	4000	22	0	0.61	2.56	4.82	1.44	0.36
0	0	0	23	0	0.16	1.44	2.89	1.44	0.43

[a]Relative degree of leaf-symptom development for the experiment.

[b]Minor-element contents were determined for one replication only.

mical composition of the leaves at the end of flowering for Entry 1

:a	%Mg	Mn[b] (ppm)	B (ppm)	Zn (ppm)	Ba (ppm)	Fe (ppm)	Cu (ppm)	Mo (ppm)
;6	0.48	62	66	51	19	144	12	1.3
)8	0.56	78	67	57	13	94	10	1.2
;2	0.38	63	66	55	13	130	10	0.8
)3	0.60	101	84	52	50	124	9	2.6
14	0.71	61	65	39	32	145	8	3.2
)7	0.37	94	73	50	27	151	8	1.0
;4	0.36	59	64	40	21	200	8	0.8
;4	0.43							

element was involved. Ca and Mg deficiency may be eliminated on the same grounds as K deficiency. Induced Zn or Fe deficiency would represent the most likely remaining alternative cause of the symptoms. A possibility exists also that a higher than normal Zn content is required at elevated P levels. Zn deficiency would show by interveinal chlorosis and necrosis of lower leaves similar to the presumed P toxicity symptoms. The leaves would, however, be expected to remain small whereas they were actually larger than those of unfertilized plants. One replication of the experiment was sprayed with a mixture of "Nu-Zinc" and "Nu-Iron" after removal of all pots which were to be harvested at the seven-leafed stage. No improvement was observed on any previously affected leaf and no differences developed in the condition of the plants between the sprayed and the unsprayed blocks in the trial to the end of flowering or thereafter.

Zn and other trace elements were determined spectrographically at the Ohio Agricultural Experiment Station, Wooster. Leaves sampled at the end of flowering were analyzed. The leaves were cleaned and rinsed with deionized water before drying. It was found that the Zn content of the leaves ranged from 39 to 57 ppm (Table 93).

Viets _et al._ (1954) analyzed the youngest mature leaflet and petioles of plants growing on Zn-deficient soil treated with 23 lbs. of Zn per acre for Zn and found a content of 16.3 ppm. On non-deficient soil treated with Zn the content was 24.3 ppm. In an accompanying pot experiment these authors added 2 ppm Zn as $ZnSO_4 \cdot 7H_2O$ to Zn deficient soil and thereby increased the concentration of soybean leaves from 27 to 45 ppm Zn. Both treatments were healthy and there was no response to Zn added. By these standards the Zn contents of the present trial were sufficient for normal growth.

The Fe content of the unsprayed leaves varied between 94 and 200 ppm. Brown <u>et al</u>. (1959) reported a range of 43 to 85 ppm Fe in tops of Hawkeye soybeans grown in the greenhouse. These plants had a very limited supply of Fe from soil and were healthy. Total Fe in the plant is not a very meaningful criterion because a low efficiency of Fe utilization may render nearly any amount ineffective in the plant. No Fe-inefficient varieties were involved in the present experiment, but sufficient Fe could be inactivated by high P applications to result in leaf symptoms. Bennett (1945) suggested that Fe in leaf tissues is particularly susceptible to precipitation changes induced by P treatments. Spraying with Nu-Iron more than doubled the Fe-content of the leaves. No visible results emanated from the spray treatment and since iron deficiencies can be rather easily corrected by foliar application it was assumed that no Fe-chlorosis was involved in the symptoms.

The Mn and B contents in Table 93 reached the highest values for the P treatments resulting in leaf discoloration. The uptake of Mn is reputed to fluctuate sharply with fertilization and liming. Fletcher (1961) reported increased Mn contents in the leaves of soybeans when P was applied. In one trial the Mn content of 100 ppm was tripled by a rate of 1120 pp2m P. According to Snider (1943) leaves from "mature" and healthy soybean plants contained 98 to 191 ppm Mn on soils limed to a pH of 6.3 to 6.4. Morris and Pierre (1949) reported a range of 40 to 2168 ppm Mn in plants grown in nutrient solution. Toxicity symptoms occurred from 527 ppm up. It is clear that Mn toxicity was not involved in the present experiment. Moreover the symptoms bear no resemblance to those illustrated by Morris and Pierre for Mn toxicity.

Ohlrogge (1960) summarized a review of literature on B contents of soybean plants by stating that extremes range from 10 to over 2000 ppm with concentrations between 20 and 100 ppm indicating normal conditions. The B content of the leaves of Entry 1 in the present experiment ranged from 65 to 84 ppm (Table 93).

The contents of Ba, Cu, Mo and other elements also bore no relation to the P toxicity symptoms described.

2. Yield of soybeans and seed size as a function of fertilizer input variables

The analyses of variance of the three multiple regressions for the yield of soybeans showed highly significant fertilizer effects (F values 47.86, 52.25 and 25.75 for Entries 1, 2 and 3 respectively). The yield of all 3 lines was strongly affected by P and K application. The partial regression coefficients for the linear and quadratic effects of P and K, and the PK interaction reached the 0.01 or 0.05 level of significance (Table 94). Entry 3 was also affected by the PCa interaction effect at a probability level of 0.05 to the PCa interaction at the 0.05 level of significance according to Williams' test.

Maintaining individual estimates for the P and PCa effects for each

Table 94. Partial regression coefficients relating the yield of soybeans and seed size of two lines grown in pots in 1963, to fertilization; their level of significance and significant differential effects between lines

Dependent variable	Factor	Entry 1	Entry 2	Entry 3	MS	F
Yield	b_o	32.0194**	27.7944**	26.9635**	17.1810	< 1
	P	30.2488**	37.5727**	28.1370**	94.8262	2.039+
	K	7.5200*	8.5818*	9.7150*	4.9799	< 1
	Ca	1.9408	-1.6386	0.3162	13.3434	< 1
	P^2	-6.3711**	-6.6274**	-6.7265**	2.9102	< 1
	K^2	-2.4606**	-2.3658**	-2.5679*	0.8805	< 1
	Ca^2	-0.4971	0.6967	-0.0387	31.2354	< 1
	PK	2.8282**	2.3380**	2.7180**	7.8108	< 1
	PCa	0.7047	-0.1906	2.0030*	150.2005	3.230*
	KCa	0.3465	-0.1419	0.3745	11.2285	< 1
	PKCa	-0.1190	-0.0076	-0.3419	30.2325	< 1
	R^2	0.9319	0.9372	0.8803		
	Experimental error				46.5067	
Seed size	b_o	15.1430**	9.8935**	14.3762**	18.7925	37.924**
	P	3.3030**	1.1133**	1.7256**	4.9355	9.960**
	K	1.3517*	0.6066*	0.0631	1.72972	3.491*
	Ca	0.0726	0.0016	-0.0471	0.0151	< 1
	P^2	-0.5729**	-0.1588*	-0.4278**	3.9063	7.883 **
	K^2	-0.2816*	-0.1557*	0.0454	2.3428	4.728 *
	Ca^2	0.0429	-0.0051	0.0087	0.0526	< 1
	PK	0.0716	0.1214*	0.0680	0.0105	< 1
	PCa	-0.2134*	-0.0100	0.1207	3.4999	7.063**
	KCa	0.0365	0.0050	-0.0450	0.2249	< 1
	PKCa	0.0372	-0.0084	0.0135	0.5427	1.095
	R^2	0.8156	0.8478	0.7905		
	Experimental error				0.4955	

line the yield equations were combined in the equation given in Table 95.

The factors reaching significance were the same as in the individual equations and the level of significance was 0.01 in all cases. Differential effects due to P and PCa were now tested by Duncan's multiple range procedure. It appeared that highly significant differences existed among the responses of all three lines to P. Also the response of Entry 3 to the PCa interaction was highly significantly different from that of Entry 1 and Entry 2. The Ca and PCa terms could further be deleted from the equation for Entries 1 and 2 if final prediction equations were required. The overall effect of fertilizer on seed size reached significance at the 0.01 level in the three regression analyses for the individual soybean lines.

The linear and quadratic effects of P exerted the strongest influence and were highly significant. In addition, the K and K^2 as well as the PK and PCa effects reached the 0.05 level of significance in some varieties. Strong differential effects at the 0.01 and 0.05 level were due to P, P^2, K, K^2 and the PCa interaction (Table 94). The same or somewhat higher significance levels were obtained in the equation for the three varieties combined (Table 95).

Duncan's procedure using the coefficients of the combined equation showed highly significant varietal differences in seed size. This only confirmed a known fact. Entry 1 is a large-seeded and Entry 2 a small-seeded line. Many strong differential responses to fertilizers were found. Entry 1 had the strongest linear and quadratic effects from P application and differed at the 0.01 level from Entry 2 in this respect.

Table 95. Partial regression coefficients of the combined equations for yield of soybeans and seed size and their significance

Yield			Seed size		
Factor	b_i	<u>t</u>	Factor	b_i	<u>t</u>
b_o	28.0811	13.03**	V_1	15.2966	49.40**
$V_1 \times P$[a]	32.8963	17.62**	V_2	9.7997	31.65**
$V_2 \times P$	36.4962	19.55**	V_3	14.3146	46.23**
$V_3 \times P$	28.4366	15.23**	$V_1 \times P$	3.0070	9.88**
K	8.9382	5.23**	$V_2 \times P$	1.1598	3.81**
Ca	0.8065	1.29	$V_3 \times P$	1.6839	5.53**
P^2	-6.5571	16.43**	$V_1 \times K$	1.4514	4.88**
K^2	-2.4462	6.14**	$V_2 \times K$	0.5848	1.96++
PK	2.2672	9.50**	$V_3 \times K$	-0.0915	0.31
$V_1 \times PCa$	0.2996	0.93	Ca	0.0686	1.07
$V_2 \times PCa$	-0.1661	0.05	$V_1 \times P^2$	-0.5667	7.95**
$V_3 \times PCa$	1.3333	4.13**	$V_2 \times P^2$	-0.1579	2.22*
			$V_3 \times P^2$	-0.4194	5.88**
			$V_1 \times K^2$	-0.2668	3.75**
			$V_2 \times K^2$	-0.1574	2.21*
			$V_3 \times K^2$	0.0884	0.68
			$P \times K$	0.1215	4.93**
			$V_1 \times P \times Ca$	-0.0567	1.70++
			$V_2 \times P \times Ca$	-0.0505	1.52+
			$V_3 \times P \times Ca$	0.0996	2.99**
R^2	0.9158		R^2	0.9532	

[a]The variety effects of Entries 1, 2 and 3 are hereafter indicated by the symbols V_1, V_2 and V_3.

Table 96. Comparison of corresponding partial regression coefficients in the combined equations for yield and seed size for three soybean lines using Duncan's multiple range test

Dependent variable	Nature of differential response	Line, regression coefficients and significance of differences[a]		
Yield	P	3	1	2
		28.4366	32.8963	36.4962
	PCa	2	1	3
		-0.0166	0.2996	1.3333
Seed size	Variety	2	3	1
		9.7997	14.3146	15.2966
	P	2	3	1
		1.1591	1.6839	3.0070
	K	3	2	1
		-0.0915	0.5848	1.4514
	P^2	1	3	2
		-0.5667	-0.4194	-0.1579
	K^2	1	2	3
		-0.2668	-0.1574	0.0484
	PCa	1	2	3
		-0.0567	-0.0505	0.0996

[a]Comparisons failing to reach the 0.05 level of significance are underlined with a solid line. In addition, those reaching the 0.05 level but not the 0.01 level of significance are underlined with a broken line.

Entry 1 also had the largest effects of K and K^2 and differed in this from the other lines. It differed from Entry 3 at the 0.01 level and from Entry 2 at the 0.05 level with respect to K and at the 0.01 level with respect to K^2. Entry 2 differed from Entry 3 at the 0.05 level with respect to K^2. Entry 3 differed from the other lines at the 0.01 level of significance with respect to PCa.

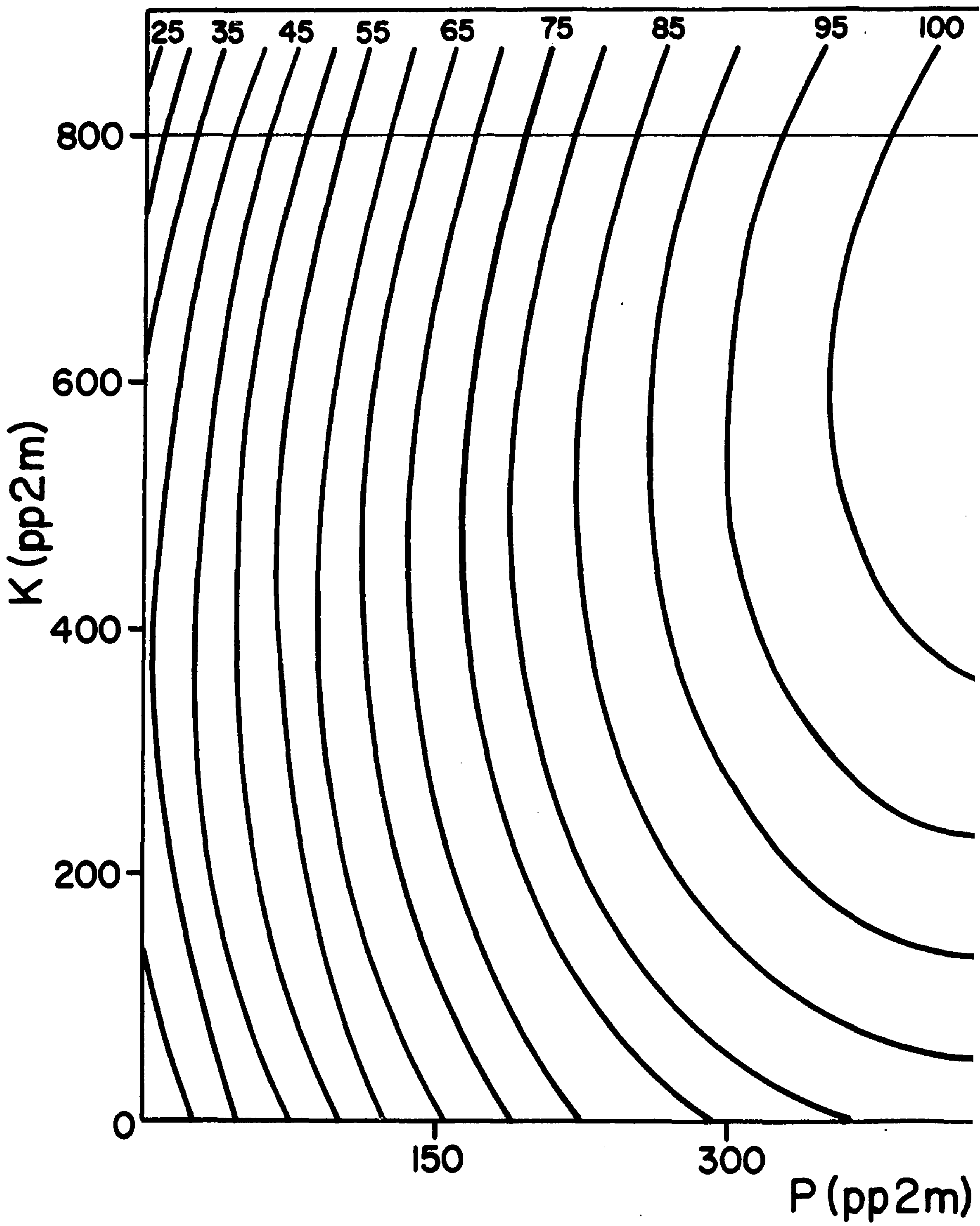
Yield isoquant maps for the Entries 2 and 3 were reproduced since it appeared from Table 96 that the widest differential responses occurred between these two lines (Figures 31 and 32). Starting from the same yield when unfertilized Entry 2 reached a considerably higher maximum due to larger response to fertilization.

Figures 31 and 32 show very strong responses to P and also to K, at higher levels of P. The response to K is noteworthy because the soil used in the experiment had a medium content of available K. The strongest differential responses in seed size occurred between the lines Entry 1 and Entry 2 and isoquant maps for these two lines illustrate the varietal differences and responses and differential responses clearly (Figures 33 and 34). Whereas differential responses in favor of Entry 2 resulted in higher yields for this line than for the other two over the entire region of P and K investigated, it appears that Entry 1 had the largest seed size.

Predicted yield responses to 300 pp2m P exceeded 100% when 400 pp2m K and 2000 pp2m Ca were applied. There was also a considerable differential response between the 2 lines as shown in Table 97. The response to 400 pp2m K at 300 pp2m P and 2000 pp2m Ca was appreciable when the

Figure 31. Yield isoquants for Entry 2 in 1963 expressed in grams of soybeans per pot as a function of P and K, holding Ca constant at 2000 pp2m

——————— Limits of investigated area


25
35
45
55
65
75
85
95
100
800
600
400
200
0
K (pp2m)
150
300
P (pp2m)

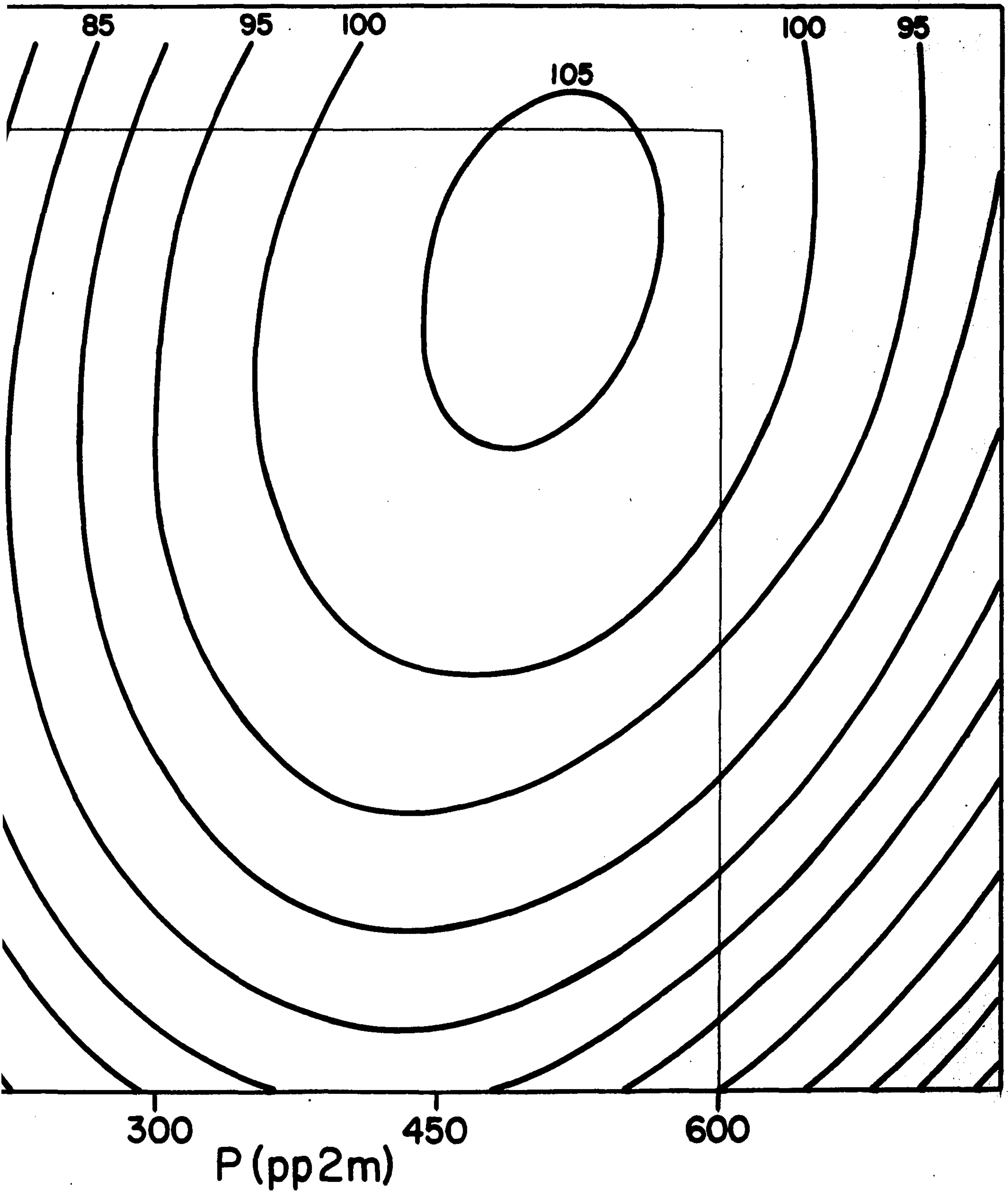
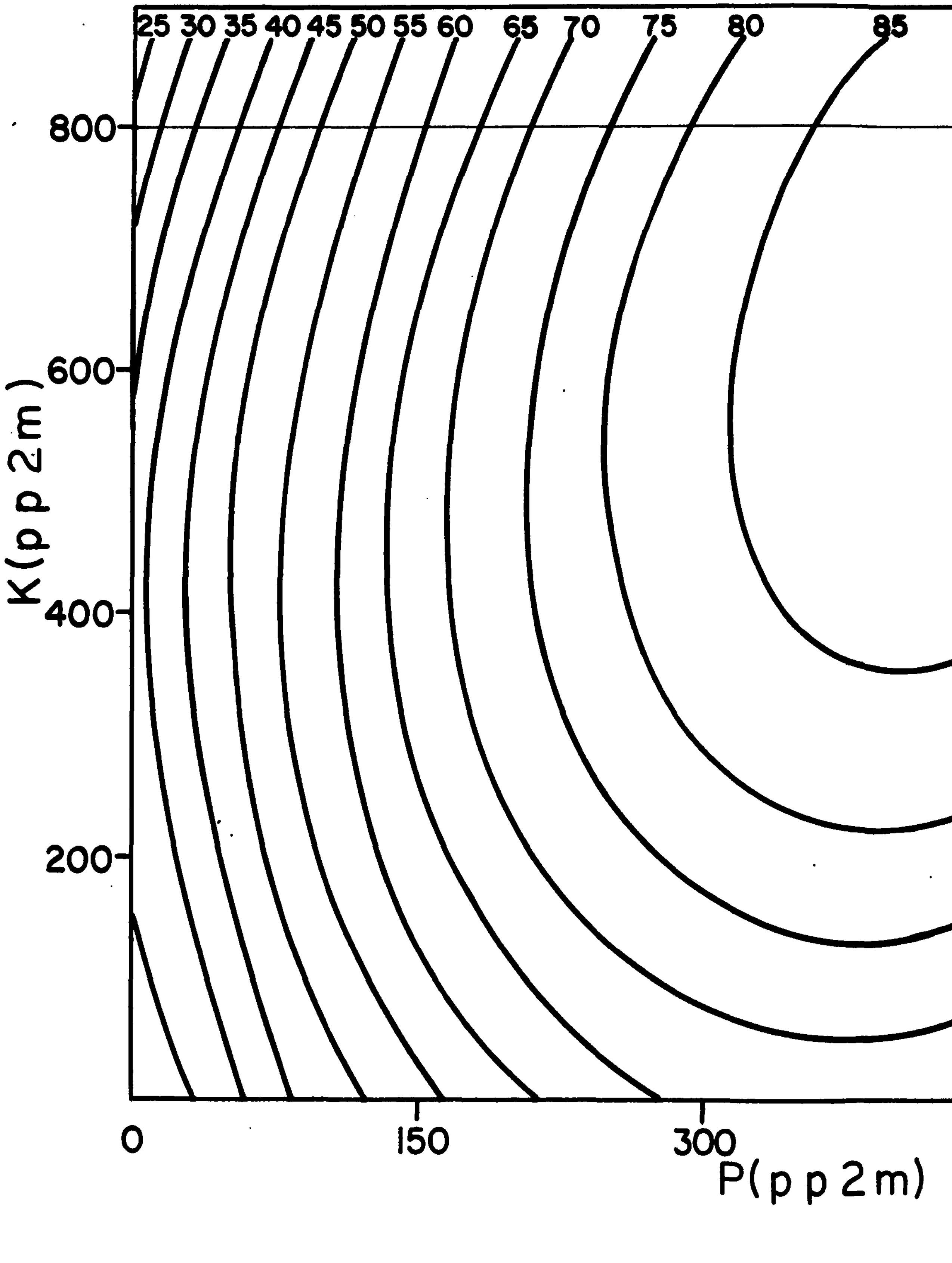
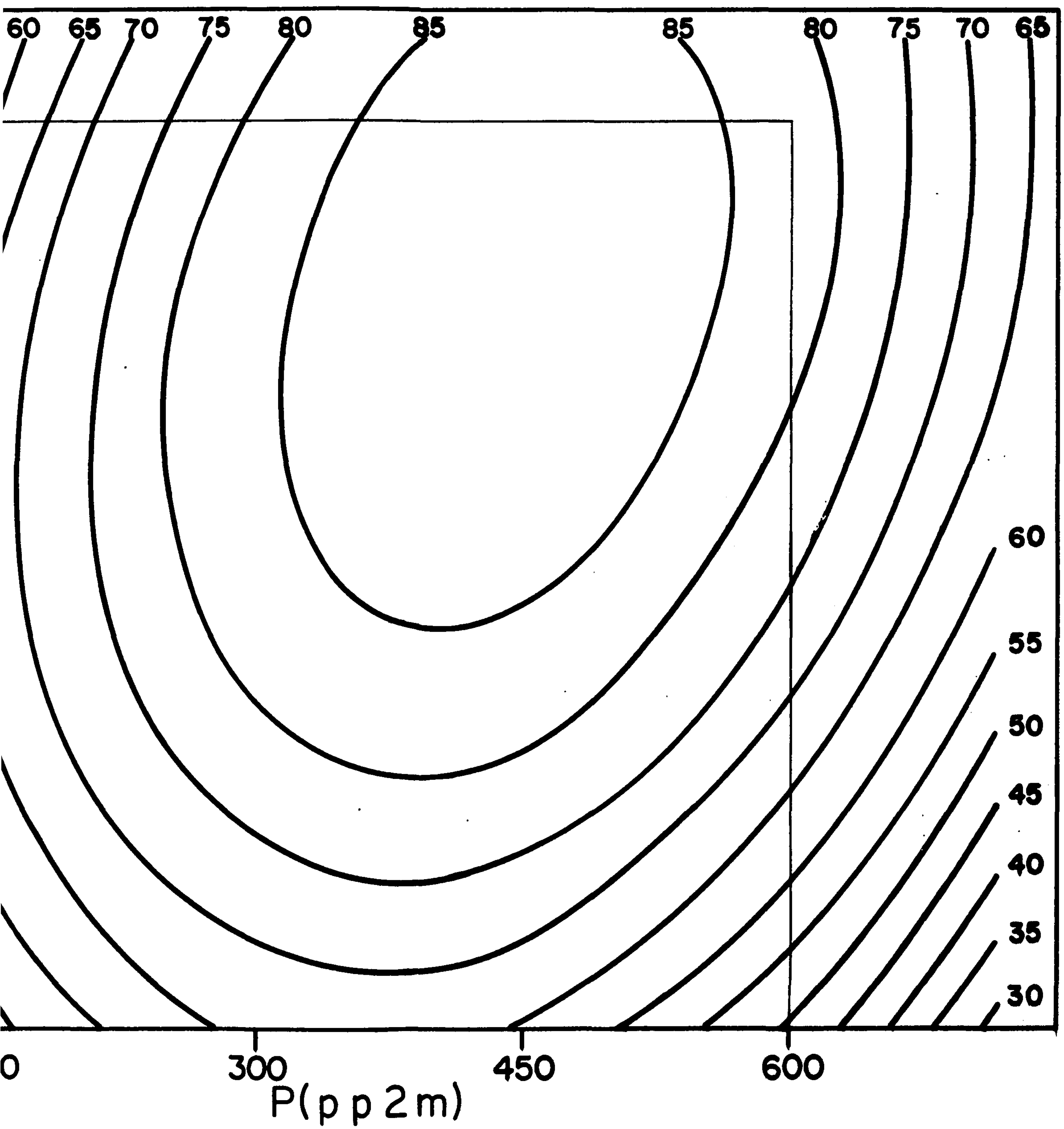

85
95
100
105
100
95
300
450
600
P (pp2m)

Figure 32. Yield isoquants for Entry 3 in 1963 expressed in grams of soybeans per pot as a function of P and K, holding Ca constant at 2000 pp2m

———————— Limits of investigated area

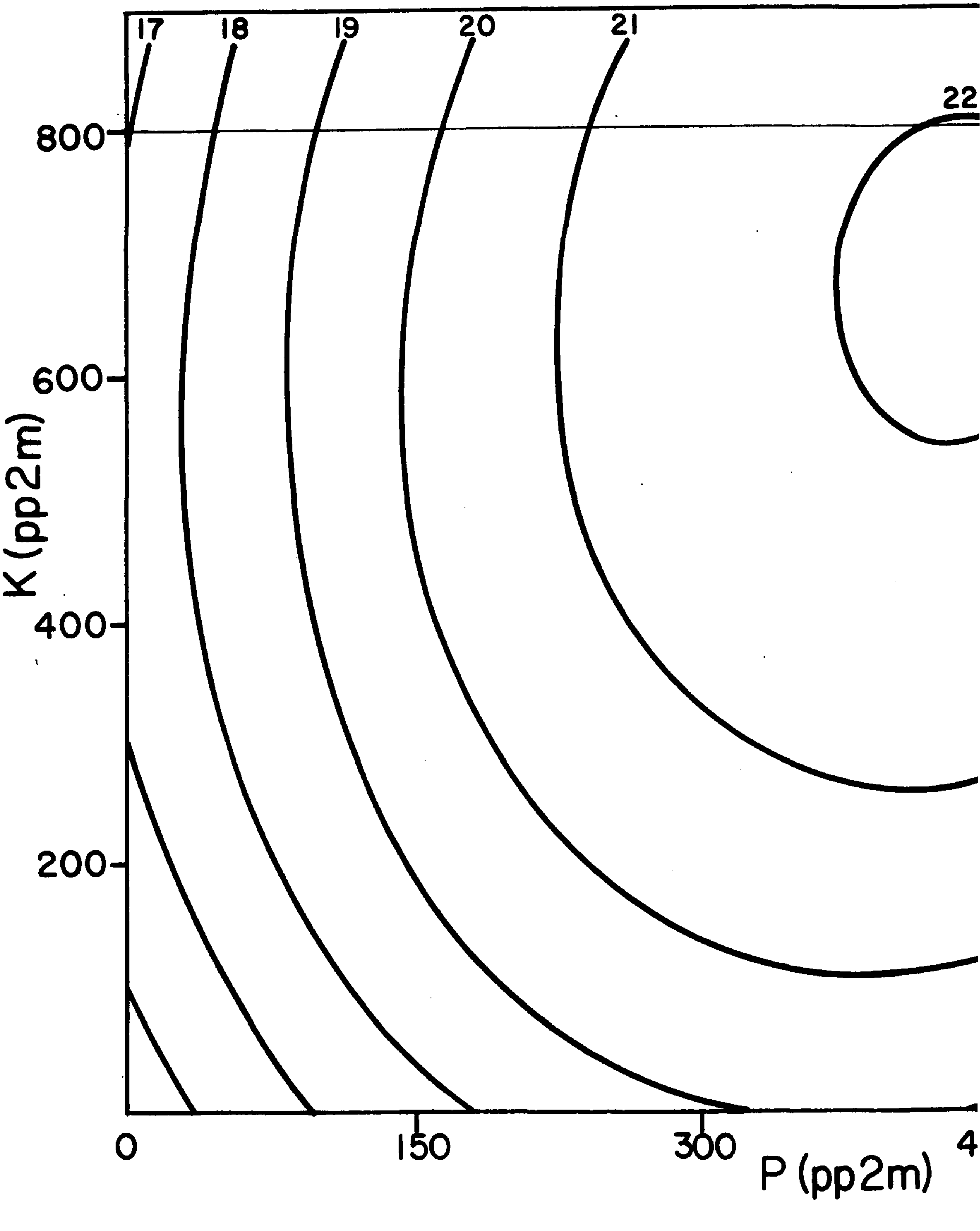

25
30
35
40
45
50
55
60
65
70
75
80
85
800
600
400
200
K(p p 2m)
0
150
300
P(p p 2m)



60
65
70
75
80
85
85
80
75
70
65
60
55
50
45
40
35
30
0
300
450
600
P(pp2m)

Figure 33. Isoquants of seed size expressed in grams per 100 seeds for Entry 1, grown in pots in 1963, as a function of P and K, holding Ca constant at 2000 pp2m

——————— Limits of investigated area


17
18
19
20
21
22
800
600
400
200
K (pp2m)
0
150
300
4
P (pp2m)

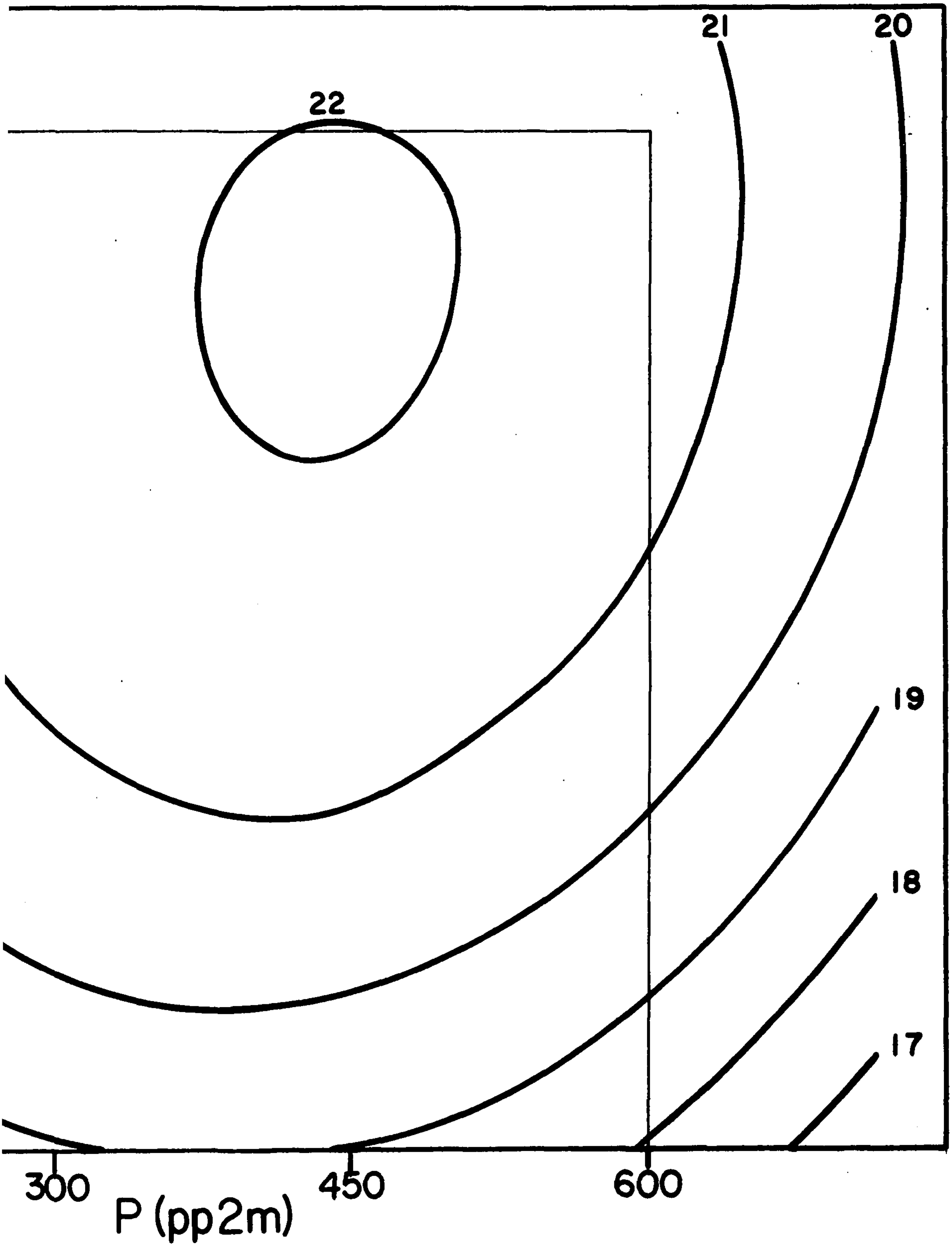
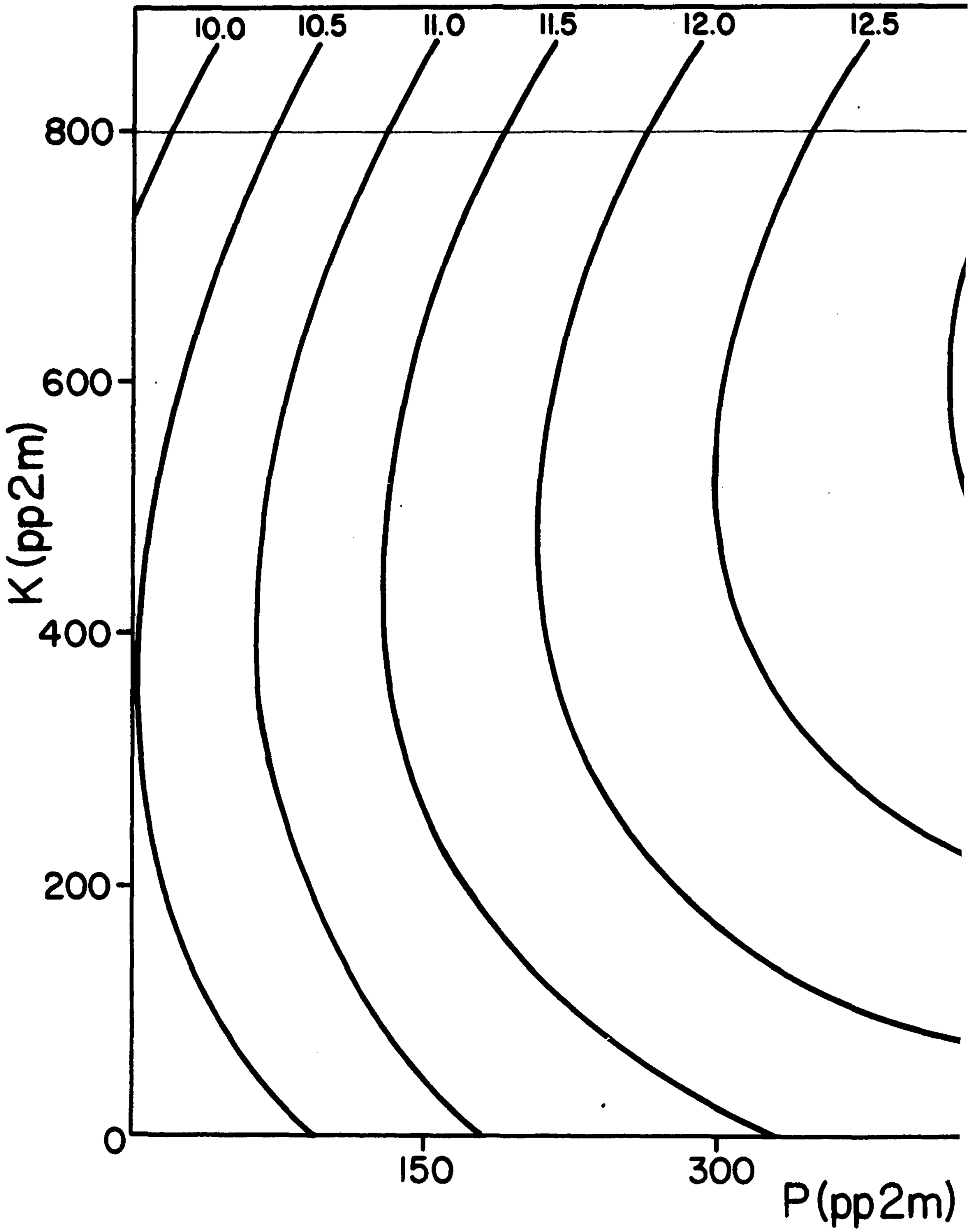
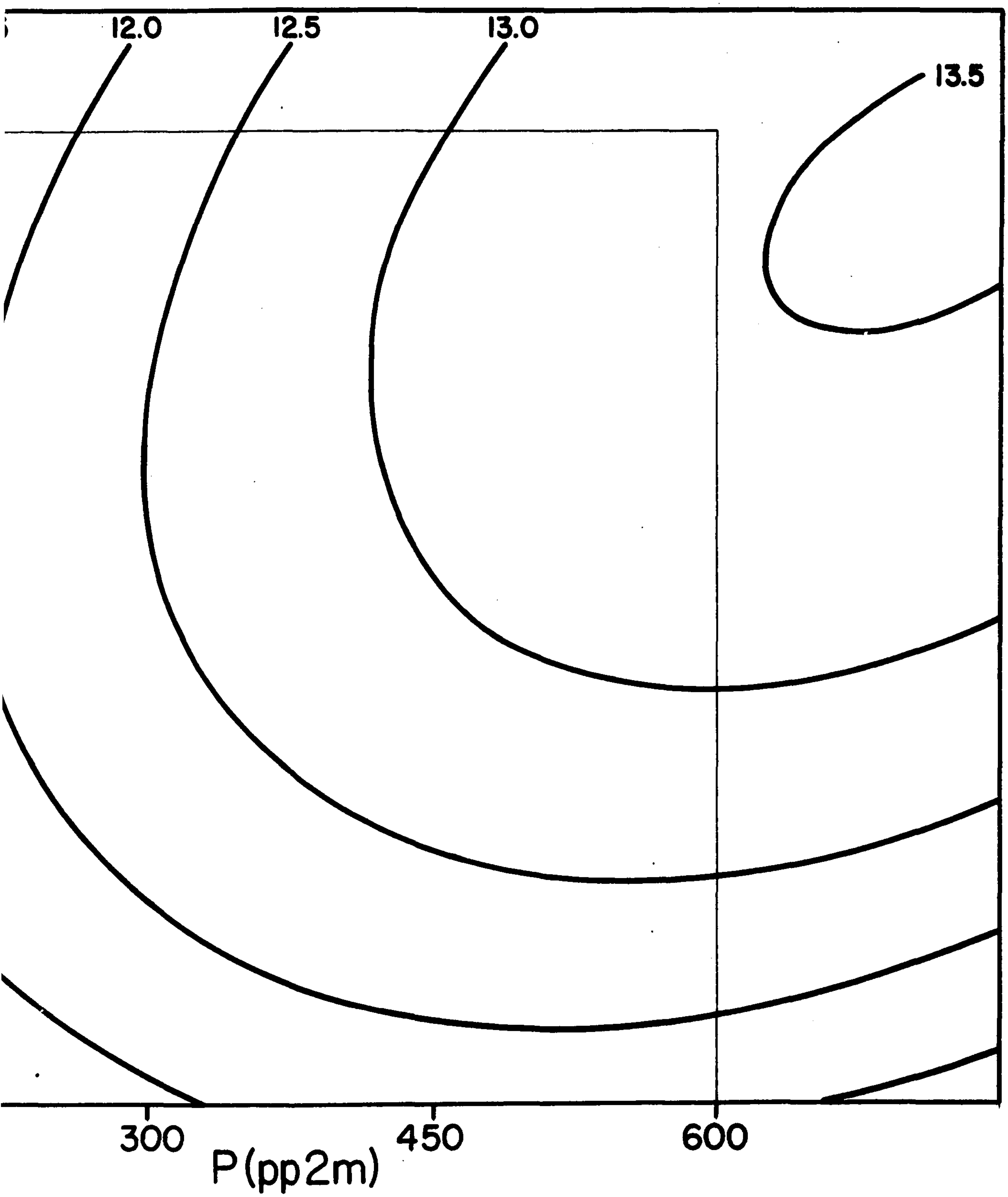

22
21
20
19
18
17
300
450
600
P (pp2m)

Figure 34. Isoquants of seed size expressed in grams per 100 seeds for Entry 2, grown in pots in 1963 as a function of P and K, holding Ca constant at 2000 pp2m

——————— Limits of investigated area


10.0
10.5
11.0
11.5
12.0
12.5
800
600
400
200
0
K (pp2m)
150
300
P (pp2m)



12.0
12.5
13.0
13.5
300
450
600
P (pp2m)

medium level of initial K fertility of the soil is considered.

The seed size responses in Table 97 were quite large considering the less flexible nature of this property. Differential responses of approximately two thirds the size of the P and K responses were obtained between the three lines.

The combination of P, K and Ca for maximum yield as determined by approximation from several isoquant maps shows the high amounts of all three elements required for maximum yield which conforms closely with the optimum for production of dry matter at the 4.5-leafed stage in the previous pot experiment (Table 98).

The experiment predicts that the yield of soybeans can be more than tripled for all three varieties by fertilization.

It may be noted that the fertilizer combination for maximum yield is also close to the optimum for seed size. The maximum is nearly independent of Ca and small differences in equations of individual varieties may change the required rate of Ca from one end of the range to the other. This caused the maximum to be located at 4000 pp2m Ca for Entry 1 and at 0 Ca for Entry 2.

The critical percentages of nutrients in the leaves at the end of flowering will be discussed in the section on leaf composition.

3. Growth characteristics at three stages of development as a function of fertilizer input variables

a. Fresh-weight production of plant tops F-values between 5 and 65 were calculated when testing the total variation explained by the

Table 97. Magnitude of predicted responses and differential responses of soybean yield and seed size to P and K fertilization involving one or more significant effects

Dependent variable	Entry	Factor specification (pp2m)			Yield or seed size			Largest differential response
		P	K	Ca	from	to	response	
Yield (gms./pot)	1	0-300	400	2000	42	87.0	45.0	
	2	0-300	400	2000	40	93.0	53.0	
	3	0-300	400	2000	39	82.0	43.0	10
	1	300	0-400	2000	70	88.0	18.0	
	2	300	0-400	2000	75	93.0	18.0	
	3	300	0-400	2000	65	82.0	17.0	
Seed size (gms./100 seeds)	1	0-300	400	2000	17.3	21.3	4.0	
	2	0-300	400	2000	10.5	12.5	2.0	2.0
	1	300	0-400	2000	19.3	21.3	2.0	
	2	300	0-400	2000	11.4	12.5	1.1	0.9

Table 98. Fertilizer combination for maximum yield, maximum yield of soybeans in grams per pot and seed size expressed as grams per 100 seeds, and ratio of predicted yields at the maximum and at no fertilization for three soybean lines, grown in pots in 1963

Dependent variable	Entry	Combination at maximum (pp2m)			$\hat{Y}_{max}$	$\hat{Y}_{max} / \hat{Y}_{check}$
		P	K	Ca		
Yield	1	480	660	3700	100	3.33
	2	510	680	4000	108	3.60
	3	451	640	4000	98	3.27
Seed size	1	420	670	4000	22.4	1.48
	2	600	740	0	13.8	1.40

multiple regressions for the fresh weight of tops at three stages of development. They indicate very high levels of significance for the effect of fertilizers. P had the strongest influence on the rate of growth and the partial regression coefficients for P and P^2 reached the 0.01 level of significance in all cases (Table 99).

The linear and quadratic effects of K were significant for Entry 1. Other factors which reached the 0.05 level of significance at times in the Entries 1 and 3 were the PK and PCa interactions. The R^2 values were high for the data recorded at the end of flowering and low at the two-leafed stage. It is thought that the low R^2 values were at least partly caused by weighing of small amounts of fresh material which had to be performed in the field. Highly significant differential effects were found with respect to P and P^2. Differential effects due to PCa reached

Table 99. Partial regression coefficients relating the fresh weight of plant tops of three soybean lines, grown in pots in 1963 and harvested at three stages of development, to fertilization; their significance and significant differential effects between lines

Stage of development	Factor	Entry 1	Entry 2	Entry 3	Mean squares	F
End of flowering	b_o	243.7948**	326.3820**	238.7153**	5661.1070	3.509*
	P	153.4294**	293.9871**	154.9699**	25189.9802	15.613**
	K	41.3804**	-4.4958	20.2569	2179.1678	1.351
	Ca	4.5164	5.1001	44.4903+	2180.7929	1.352
	P^2	-28.8278**	-56.8616**	-43.2497**	17003.6512	10.539**
	K^2	-10.1777**	-0.8969	-5.3677	1855.2913	1.150
	Ca^2	1.6267	-2.1241	-9.3495+	2680.6042	1.661+
	PK	4.2209+	2.2160	11.8570*	3056.2615	1.894+
	PCa	2.7373	1.4220	13.9992*	5900.7107	3.657*
	KCa	-1.4672	3.0289	-1.1542	839.0789	< 1
	PKCa	-1.3971+	-0.4855	-0.4798	290.8437	< 1
	R^2	0.9279	0.8682	0.8424		
	Experimental error				1613.3750	
Seven-leafed stage	b_o	117.0754**	68.3968**	101.9725**	1451.1388	7.373**
	P	27.3283**	28.5421**	51.6775**	728.0280	3.699*
	K	8.8267+	-6.3041	3.1545	34.8416	< 1
	Ca	6.9645	6.3305	4.1254	9.2254	< 1
	P^2	-6.1245**	-6.8656**	-14.3666**	1798.8493	9.140**
	K^2	-2.0142+	1.8835+	0.1785	328.7953	1.671+
	Ca^2	-2.0099+	-1.6803	-0.3080	70.1661	< 1

Table 99. (Continued)

Stage of development	Factor	Entry 1	Entry 2	Entry 3	Mean squares	F
	PK	1.2839	1.0382	3.0340+	139.8714	< 1
	PCa	2.8684*	1.5343	4.6842*	308.6477	1.568+
	KCa	-0.0053	0.2342	-0.6733	29.4510	< 1
	PKCa	-0.0181	-0.4030	-0.7781	150.6766	< 1
	R^2	0.8397	0.6082	0.7501		
	Experimental error				196.8126	
Two-leafed stage	b_o	23.1044**	16.3561**	21.2697**	28.4573	5.317**
	P	5.5962**	5.1414**	4.8793**	0.5438	< 1
	K	-0.0458	0.2567	2.1070+	5.6137	1.049
	Ca	-1.6920	-0.6249	-1.1671	1.1820	< 1
	P^2	-0.9131**	-0.9544**	-1.0830**	0.6792	< 1
	K^2	-0.1101	-0.0417	-0.2661	1.1393	< 1
	Ca^2	0.2043	0.1529	0.3303	0.7174	< 1
	PK	0.1718	-0.0209	0.0921	1.1072	< 1
	PCa	0.0567	-0.0748	0.2639	3.5997	< 1
	KCa	0.3340+	-0.1445	-0.4062+	18.7591	3.505*
	PKCa	-0.0801	0.0309	0.0346	4.4328	< 1
	R^2	0.6656	0.5799	0.5936		
	Experimental error				5.3518	

the 0.05 level of significance at two stages of development. Weaker suggestions of differential behavior were found for K^2, Ca^2 and the PK interaction.

Combination of the data according to the differences found between the three varieties resulted in three regression equations which are shown in Table 100. The distribution of significant coefficients remained practically the same as in the original equations for the end of flowering. In some cases the level of significance was raised. The same applied to the equation referring to the seven-leafed stage with the exception that the coefficients for K and K^2 lost all significance. Duncan's multiple range test revealed a large number of differential effects at the 0.01 and 0.05 level of significance.

As may be seen from Table 101 the differential effects were entirely due to some or all of the following effects: P, P^2, PK and PCa.

Suggestions of differences in response to Ca^2, K^2 and the KCa interaction in the original equations were not substantiated. Another meaningful finding is that no significant differential responses to fertilization occurred at the two-leafed stage. The same variety does not necessarily stand out from the others in response to a certain effect at all stages of growth. An example of this are the varietal differences. At the two- and seven-leafed stages Entry 2 had the smallest coefficient for the intercept which indicates the lowest benefit from a conglomerate of undefined varietal characteristics. At the end of flowering the situation was reversed and Entry 2 was shown by Duncan's test to have the highest production of fresh weight of tops at the 0.01 level of significance.

Table 100. Partial regression coefficients, b_i, of the combined equations for fresh weight production of plant tops at three stages of development in 1963, *t*-values and their significance

End of flowering			Seven-leafed stage			Two-leafed stage		
Factor	b_i	*t*	Factor	b_i	*t*	Factor	b_i	*t*
V_1	248.4020	13.59**	V_1	116.1508	19.41**	V_1	21.7952	28.68**
V_2	306.4856	16.76**	V_2	67.4238	11.27**	V_2	15.0199	19.76**
V_3	252.3639	13.80**	V_3	105.3283	17.60**	V_3	21.3300	28.07**
V_1xP	157.3891	8.87**	V_1xP	34.6293	5.97**	P	5.2947	11.06**
V_2xP	279.4194	15.74**	V_2xP	25.5664	4.40**	K	0.3585	1.59+
V_3xP	165.9931	9.35**	V_3xP	53.3282	9.19**	Ca	0.0060	0.03
K	19.3234	1.81++	K	1.6491	0.44	P^2	-0.9250	8.07**
Ca	18.3009	1.72++	Ca	5.5108	1.48+	V_1xKCa	-0.0316	0.32
V_1xP^2	-29.2837	7.72**	V_1xP^2	-7.4268	5.61**	V_2xKCa	-0.1614	1.65+
V_2xP^2	-53.6917	14.16**	V_2xP^2	-5.9382	4.49**	V_3xKCa	-0.0292	0.30
V_3xP^2	-45.9641	12.12**	V_3xP^2	-13.9915	10.58**			
K^2	-5.4811	2.19*	V_1xK^2	-0.1317	0.14			
V_1xCa^2	-2.2145	0.80	V_2xK^2	-0.2050	0.22			
V_2xCa^2	-3.4614	1.25	V_3xK^2	0.3849	0.42			
V_3xCa^2	-4.1666	1.50+	Ca^2	-1.3329	1.53+			
V_1xPK	2.6009	1.15	PxK	0.7892	1.61+			
V_2xPK	3.3691	1.49+	V_1xPxCa	2.3101	3.34**			

Table 100. (Continued)

End of flowering			Seven-leafed stage			Two-leafed stage		
Factor	b_i	*t*	Factor	b_i	*t*	Factor	b_i	*t*
V_3xPK	12.1162	5.35**	V_2xPxCa	0.6203	0.90			
V_1xPCa	1.9164	0.69	V_3xPxCa	3.7583	5.43**			
V_2xPCa	1.7312	0.62						
V_3xPCa	14.3036	5.12**						
PxKCa	-0.7528	1.50+						
R^2	0.9255			0.8724			0.7379	

Table 101. Comparison of corresponding partial regression coefficients of the combined equations for fresh-weight production of plant tops for three soybean lines at three stages of development in 1963, using Duncan's multiple range test

Stage	Nature of differential response	Line, regression coefficients and significance of differences[a]		
End of flowering	Variety	1 248.4020	3 252.3639	2 306.4865
	P	1 157.3891	3 165.9931	2 279.4194
	P^2	2 -53.6917	3 -45.9641	1 -29.2837
	Ca^2	3 -4.1666	2 -3.4614	1 -2.2145
	PK	1 2.6009	2 3.3691	3 12.1162
	PCa	2 1.7312	1 1.9164	3 14.3036
Seven-leafed	Variety	2 67.4238	3 105.3283	1 116.1508
	P	2 25.5664	1 34.6293	3 53.3282
	P^2	3 -13.9915	1 -7.4268	2 -5.9382
	K^2	2 -0.2050	1 -0.1317	3 0.3849
	PCa	2 0.6203	1 2.3101	3 3.7583

Table 101. (Continued)

Stage	Nature of differential response	Line, regression coefficients and significance of differences[a]		
Two-leafed	Variety	2 15.0199	3 21.3300	1 21.7952
	KCa	2 -0.1614	1 -0.0316	3 -0.0292

[a]Comparisons failing to reach the 0.05 level of significance are underlined with a solid line. In addition, those reaching the 0.05 level but not the 0.01 level of significance are underlined with a broken line.

This conforms well with field observations. Entry 2 appeared spindly and belated until flowering and improved later.

Differential effects to fertilization indicated by Duncan's procedure at the end of flowering were as follows: Entry 2 exceeded the Entries 1 and 3 with respect to P responses to the 0.01 level of significance. Entry 1 differed highly significantly from Entries 2 and 3 with respect to P^2, while Entry 3 differed from Entries 1 and 2 in response to the PK and PCa interactions at the 0.01 level of significance.

At the seven-leafed stage Entry 3 stood out from the others in its response to P and P^2 at the 0.01 level of significance and also in comparison to Entry 2 involving the PCa interaction effect. The Entries 1 and 2 differed in response to PCa interaction at the 0.05 level of significance.

The magnitude of the differential responses resulting from all effects involved was determined by graphical means from isoquant maps produced. The predicted effect from application of 300 pp2m P at 400 pp2m K and 2000 pp2m Ca per acre is shown in Table 102. The responses to P were large and they were largest at the end of flowering both in absolute weights and relative to the weight of tops at 0 P application. The differential responses also were considerable. As may be expected from the effects discussed Entry 2 had a larger fresh weight production than the other lines at all fertilizer combinations in the investigated region at the end of flowering. At the seven-leafed stage a similar conclusion applied in favor of Entry 1.

The fertilizer combination for maximum production of green matter at the three stages of development are summarized in Table 103. The requirements for P and K were again high, although Entry 2 demanded less P than Entry 1 for maximum green matter production, particularly in the early stages of development. Entry 2 was selected from the 1962 field trial for its low P content in the leaves. A tendency existed for the ratio of maximum predicted yield to the yield at no fertilization to increase in later stages of growth as may be seen from the last column in Table 103.

b. Nodulation   All nodules which were sufficiently large to be seen and picked were collected, weighed and counted. Multiple regression equations were derived for the number of nodules and their fresh weight.

Tests on the overall regression of nodulation characteristics revealed lower F-values for the number of nodules than for most other aspects of this study. Most tests still indicated significance at the

Table 102. Magnitude of predicted responses and differential responses to P for the fresh weight of tops of three soybean lines, grown in pots in 1963, involving one or more significant effects

Stage of development	Entry	Factor specification (pp2m)			Weight of tops (gms./pot)			Largest differential response
		P	K	Ca	from	to	response	
End of flowering	1	0-300	400	2000	292.0	502.0	210.0	
	2	0-300	400	2000	350.0	703.0	353.0	143.0
Seven-leafed	1	0-300	400	2000	125.0	175.0	50.0	
	2	0-300	400	2000	77.0	107.0	30.0	
	3	0-300	400	2000	115.0	183.0	68.0	38.0
Two-leafed	1	0-300	400	2000	22.5	29.5	7.0	
	2	0-300	400	2000	16.0	22.0	8.0	
	3	0-300	400	2000	22.0	28.8	6.8	

Table 103. Fertilizer combination at maximum yield, maximum yield of fresh weight of tops and ratio of predicted green weights at the maximum and at no fertilization for Entries 1 and 2, grown in pots in 1963 and harvested at three stages of development

Stage of development	Entry	Combination at maximum (pp2m)			$\hat{Y}_{max}$	$\hat{Y}_{max} / \hat{Y}_{check}$
		P	K	Ca		
End of flowering	1	425	420	4000	545	1.98
	2	398	440	2850	725	2.07
Seven-leafed	1	533	800	4000	195	1.56
	2	353	800	2100	118	1.69
Two-leafed	1	503	480	0	31	1.41
	2	402	480	0	23	1.44

0.01 level, but that for Entry 2 at the seven-leafed stage reached only the 0.05 level and in the case of Entry 1 at the end of flowering the calculated F-value remained just below that level (Table 104).

It is thought that the error variance for nodule counts in this experiment was unduly high due to the fact that several persons were involved in picking large numbers of nodules. The fresh weight values were not affected by this to the same degree and the F-values were large. For this reason the partial regression coefficients for the number of nodules at the end of flowering attained only the 0.05 level of significance and this mostly for the linear and quadratic effects of P. Most other effects if they existed did not reach significance except those for K and K^2 in Entry 3. At the seven-leafed stage the PCa inter-

Table 104. F-values for the overall regression of nodule number and weight on fertilizer factors for three soybean lines grown in pots in 1963 and harvested at two stages of development; and their level of significance

Dependent variable	Stage of development	Entry 1	Entry 2	Entry 3	Tabular F_{44}^{10}	
					P(0.05)	P(0.01)
Number	End of flowering	1.94++	3.11**	3.61**	2.05	2.75
	Seven-leafed	3.64**	2.10*	4.24**		
Fresh weight	End of flowering	17.40**	15.35**	11.49**		
	Seven-leafed	14.22**	4.12**	8.31**		

Table 105. Partial regression coefficients relating the number of nodules harvested at two stages of growth for three soybean lines grown in pots in 1963 to fertilization; their level of significance and significant differential effects between lines

Stage	Factor	Entry 1	Entry 2	Entry 3	Mean squares	F
End of flowering	b_o	1577.9536**	1294.9064**	962.5915**	221748	1.94+
	P	337.5178+	398.9634*	398.1095+	4800	< 1
	K	-134.7901	122.9729	405.6809*	292582	2.56++
	Ca	92.1732	55.3267	-71.4518	30604	< 1
	P^2	-99.7877*	-73.2544*	-102.6061*	22689	< 1
	K^2	30.9863	-19.7892	-97.8998*	363014	3.17*
	Ca^2	-9.8160	-16.6911	18.2162	29448	< 1
	PK	43.5636	-25.3509	13.9495	141137	1.23
	PCa	41.8235	-0.1203	29.5498	57418	< 1
	KCa	-0.6861	-24.0951	-22.9438	73653	< 1
	PKCa	-6.6653	15.5935+	6.5129	130699	1.14
	R^2	0.3564	0.4707	0.5078		
	Experimental error				114406	

Table 105. (Continued)

Stage	Factor	Entry 1	Entry 2	Entry 3	Mean squares	F
Seven-leafed	b_o	778.5600**	313.2218**	619.4119**	130746	4.51*
	P	285.5047*	154.2289+	204.4053*	16968	< 1
	K	-97.7173	-11.8726	-77.6931	8543	< 1
	Ca	54.4629	84.9950	84.3450	1264	< 1
	P^2	-85.1260**	-43.5134*	-72.0017**	39157	1.35
	K^2	22.9277	9.7943	13.1356	4012	< 1
	Ca^2	-19.0772	-10.4489	-26.3122+	5432	< 1
	PK	18.3313	9.2437	22.1633+	5200	< 1
	PCa	48.4646*	17.0904	43.3412**	34977	1.21
	KCa	2.9619	-14.5181	5.1364	15458	< 1
	PKCa	-7.8710	-2.8800	-8.3631+	9602	< 1
	R^2	0.5100	0.3746	0.5480		
	Experimental error				29005	

action effect reached significance, while the significance level of P^2 also was higher (Table 105). Differential effects were found with respect to K and K^2. In the combined equations shown in Table 106 the significance levels were higher at the end of flowering. For those at the seven-leafed stage the level of significance of the P, K and PK effects was higher than in the original equations while that for P^2 fell to the 0.20 level. The results from Duncan's procedure, given in Table 107 indicated that all varieties differed in their number of nodules when unfertilized at both stages of development. Most of these differences reached the 0.01 level, some the 0.05 level of significance. Entry 2 had the lowest number at the seven-leafed stage. Isoquant maps showed that this held over the entire investigated region which is in agreement with the absence of any significant differential effects of fertilizers. The differences in response to K and K^2 at the end of flowering were due to differential behavior of Entries 1 and 3 and reached the 0.05 and 0.01 level of significance respectively.

Regression analysis of the results of nodule fresh weight determination also emphasized the dominant role of P. The linear and quadratic effects of P reached the 0.01 level of significance for all varieties and at both stages of development. The PCa effect reached significance at the younger stage of growth and there was a consistent suggestion of a PK interaction effect at the 0.20 level of significance at the end of flowering (Table 108). Significant differential effects were due to P^2 at both stages of development, while at the end of flowering the Ca and

Table 106. Partial regression coefficients, b_i, of the combined equations for the number of nodules at two stages of growth in 1963; t-values and their significance

End of flowering			Seven-leafed stage		
Factor	b_i	t	Factor	b_i	t
V_1	1616.79	11.85**	V_1	809.23	14.05**
V_2	1258.58	9.23**	V_2	340.91	5.92**
V_3	878.11	6.44**	V_3	560.00	9.72**
P	438.54	5.34**	P	193.77	4.08**
Ca	20.60	0.90	K	-61.53	6.22**
V_1xK	-86.04	0.66	Ca	49.20	1.15
V_2xK	60.65	0.47	P^2	-13.33	1.34+
V_3xK	359.89	2.78**	Ca^2	-5.64	0.36
V_1xP^2	-94.32	4.51**	PK	17.68	2.23*
V_2xP^2	-87.43	4.18**	PCa	36.20	4.72**
V_3xP^2	-90.23	4.32**	PKCa	-6.92	3.25**
V_1xK^2	23.70	0.76			
V_2xK^2	-20.26	0.65			
V_3xK^2	-93.03	2.99**			
PKCa	7.18	2.56*			
R^2	0.4972			0.6724	

Ca^2 effects also reached the 0.25 level of significance. The combined equation for the end of flowering confirmed the very high importance of P effects and all the interaction effects for which a weak suggestion existed in the individual regressions for varieties. In addition several Ca effects which had shown differential effects without significance of the effects themselves now reached a low level of significance. Similar

Table 107. Comparison of corresponding partial regression coefficients in the combined equations for the number of nodules on the roots of three soybean lines at two stages of development in 1963 using Duncan's multiple range test

Stage	Nature of differential response	Line, regression coefficients and significance of difference[a]		
End of flowering	Variety	3 878.11	2 1258.58	1 1616.79
	K	1 -86.04	2 60.65	3 359.89
	P^2	1 -94.32	3 -90.23	2 -87.43
	K^2	3 -93.03	2 -20.26	1 23.70
Seven-leafed	Variety	2 340.91	3 560.00	1 809.23

[a]Comparisons failing to reach the 0.05 level of significance are underlined with a solid line. In addition, those reaching the 0.05 level but not the 0.01 level of significance are indicated with a broken line.

trends existed at the seven-leafed stage (Table 109).

Duncan's procedure revealed that Entry 2 when not fertilized had a lower nodule fresh weight than the other varieties at the seven-leafed stage but a higher weight by the end of flowering. These comparisons reached the 0.01 level of significance (Table 110). The same reversing trend pertained to the green weight of plant tops.

Entry 2 similarly showed the lowest response to P at the seven-

Table 108. Partial regression coefficients relating the fresh weight of nodules recovered from the roots of six plants, grown in pots in 1963 and harvested at two stages of growth, for three soybean lines to fertilization; their level of significance and significant differential effects between lines

Stage	Factor	Entry 1	Entry 2	Entry 3	MS	F
End of flowering	b_o	13.6185**	24.5161**	17.3368**	71.7287	1.93+
	P	14.8783**	24.3357**	20.7517**	88.1573	2.37+
	K	2.5896	4.1653	4.5500	4.4596	< 1
	Ca	2.5099	-4.6574	-3.0275	58.6351	1.57+
	P^2	-2.6189**	-4.7615**	-5.1848**	163.7221	4.40*
	K^2	-0.7187	-0.9298	-0.9546	1.4468	< 1
	Ca^2	-0.6747	0.8848	0.7785	65.3846	1.76+
	PK	0.7551+	1.4089+	0.9833+	13.0081	< 1
	PCa	0.4565	0.5474	0.9018+	6.8352	< 1
	KCa	0.3008	-0.1181	-0.4651	1.9584	< 1
	PKCa	-0.2183	-0.3423+	-0.0062	30.1411	< 1
	R^2	0.8325	0.8143	0.7666		
	Experimental error				37.2505	
Seven-leafed	b_o	7.1645**	4.0790**	7.2202**	7.5538	1.90+
	P	4.2286**	3.1655**	6.4092**	10.5741	2.65++
	K	1.2154+	-0.1256	0.5512	1.8581	< 1
	Ca	0.0832	0.4046	0.2263	0.1077	< 1
	P^2	-0.9289**	-0.8859**	-1.8943**	28.1294	7.06**
	K^2	-0.3025+	0.0565	-0.0479	2.9367	< 1
	Ca^2	-0.0707	-0.1192	-0.1321	0.0903	< 1
	PK	0.2143	0.1465	0.2926	0.6312	< 1
	PCa	0.3799*	0.2108	0.5215*	2.9873	< 1
	KCa	-0.0091	-0.0647	-0.0663	0.1413	< 1
	PKCa	-0.0426	-0.0215	-0.0488	0.2137	< 1
	R^2	0.8024	0.5404	0.7036		
	Experimental error				3.9846	

Table 109. Partial regression coefficients, b_i, of the combined equations for fresh weight of nodules at two stages of growth in 1963; t-values and their significance

End of flowering			Seven-leafed stage		
Factor	b_i	t	Factor	b_i	t
V_1	14.0109	5.04**	V_1	6.9088	9.23**
V_2	26.9199	9.69**	V_2	3.7663	5.03**
V_3	17.2281	6.20**	V_3	7.0653	9.44**
V_1xP	14.3374	5.37**	V_1xP	5.2146	6.80**
V_2xP	24.9448	9.34**	V_2xP	3.1080	4.05**
V_3xP	23.5881	8.84**	V_3xP	7.3774	9.62**
K	0.1063	0.19	K	0.8474	1.76++
V_1xCa	4.2152	1.59+	Ca	-0.2846	1.56+
V_2xCa	-3.4363	1.30+	V_1xP^2	-1.0529	5.78**
V_3xCa	-2.9204	1.10	V_2xP^2	-0.8609	4.72**
V_1xP^2	-2.8244	4.62**	V_3xP^2	-1.9025	10.44**
V_2xP^2	-5.0149	8.20**	K^2	-0.1350	1.16
V_3xP^2	-5.6369	9.22**	PCa	0.2712	3.88**
V_1xCa^2	-1.0600	1.79++			
V_2xCa^2	0.3495	0.59			
V_3xCa^2	0.7992	1.35+			
PK	1.0972	3.86**			
PCa	0.7508	2.73**			
PKCa	-0.2129	2.79**			
R^2	0.8188			0.7998	

Table 110. Comparison of corresponding partial regression coefficients in the combined equations for the fresh-weight of nodules on the roots of three soybean lines at two stages of development in 1963, using Duncan's multiple range test

Stage	Nature of differential response	Line, regression coefficients and significance of differences[a]		
End of flowering	Variety	1	3	2
		14.0109	17.2281	26.9199
	P	1	3	2
		14.3374	23.5881	24.9448
	Ca	2	3	1
		3.4363	-2.9204	4.2152
	P^2	3	2	1
		-5.6369	-5.0149	-2.8244
	Ca^2	-1.0600	0.3495	0.7992
Seven-leafed	Variety	2	1	3
		3.7663	6.9088	7.0653
	P	2	1	3
		3.1080	5.2146	7.3774
	P^2	3	1	2
		-1.9025	-1.0529	-0.8609

[a]Comparisons failing to reach the 0.05 level of significance are underlined with a solid line. In addition, those reaching the 0.05 level but not the 0.01 level of significance are indicated with a broken line.

leafed stage. This differed from Entry 3 at the 0.01 and from Entry 1 at the 0.05 level of significance. By the end of flowering the highest linear effect to P was recorded for Entry 2. This differed at the 0.01 level from that for Entry 1.

Differential responses to Ca were much weaker than those to P. The only difference reaching the 0.05 level of significance was due to Ca^2 between the Entries 1 and 3 at the end of flowering.

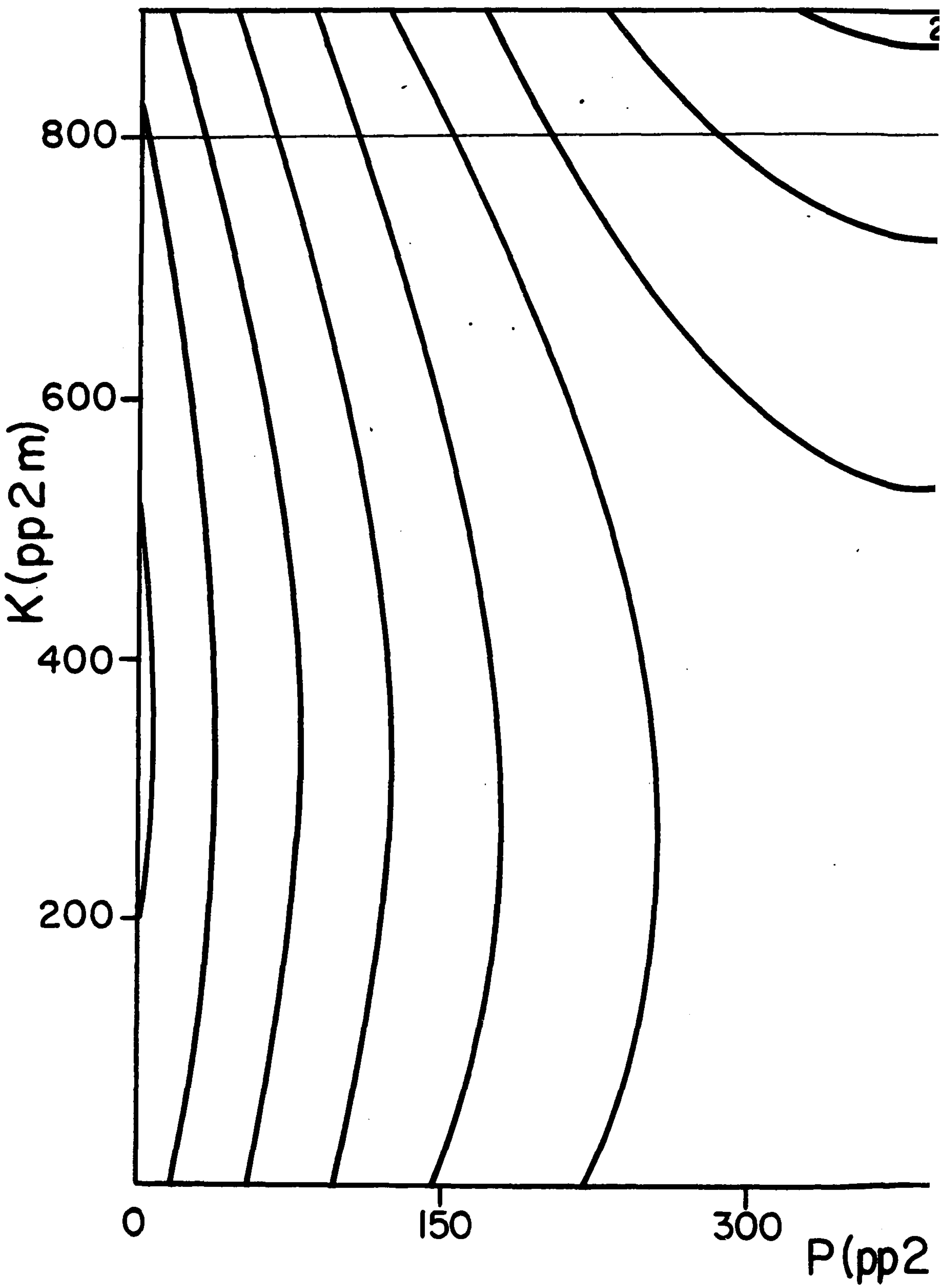
Isoquant maps for the number of nodules at the end of flowering were drawn. Those for the Entries 1 and 3 are reproduced here (Figures 35 and 36). They show the expected number of nodules under varying P and K application at a constant level of 2000 pp2m Ca.

The graphs illustrate the significant differential effects between the two lines.

The production surface for Entry 1 is of a hyperbolic nature. That for Entry 3 is ellipsoidal. The number of nodules when plotted versus P shows a maximum in the middle of the range of P for both lines at any value of K. The differential effects were due to the opposite signs of the K and K^2 coefficients in the case of the two lines. The positive K^2 coefficients for Entry 1 caused the hyperbolic shape of the isoquants. K response curves would show a minimum number of nodules at certain values of K and at any constant level of P. Those for Entry 3 would show a maximum. Entry 1 had a higher predicted number of nodules than Entries 2 and 3 over the entire investigated region of P and K. Entry 2 however, had a higher nodule fresh weight than Entry 1 irrespective of the rate of fertilization as shown in Figures 37 and 38.

Figure 35. Isoquants of number of nodules at the end of flowering for Entry 1, grown in pots in 1963, as a function of P and K, holding Ca constant at 2000 pp2m

——————— Limits of investigated area



800
600
400
200
K(pp2m)
0
150
300
P(pp2
2

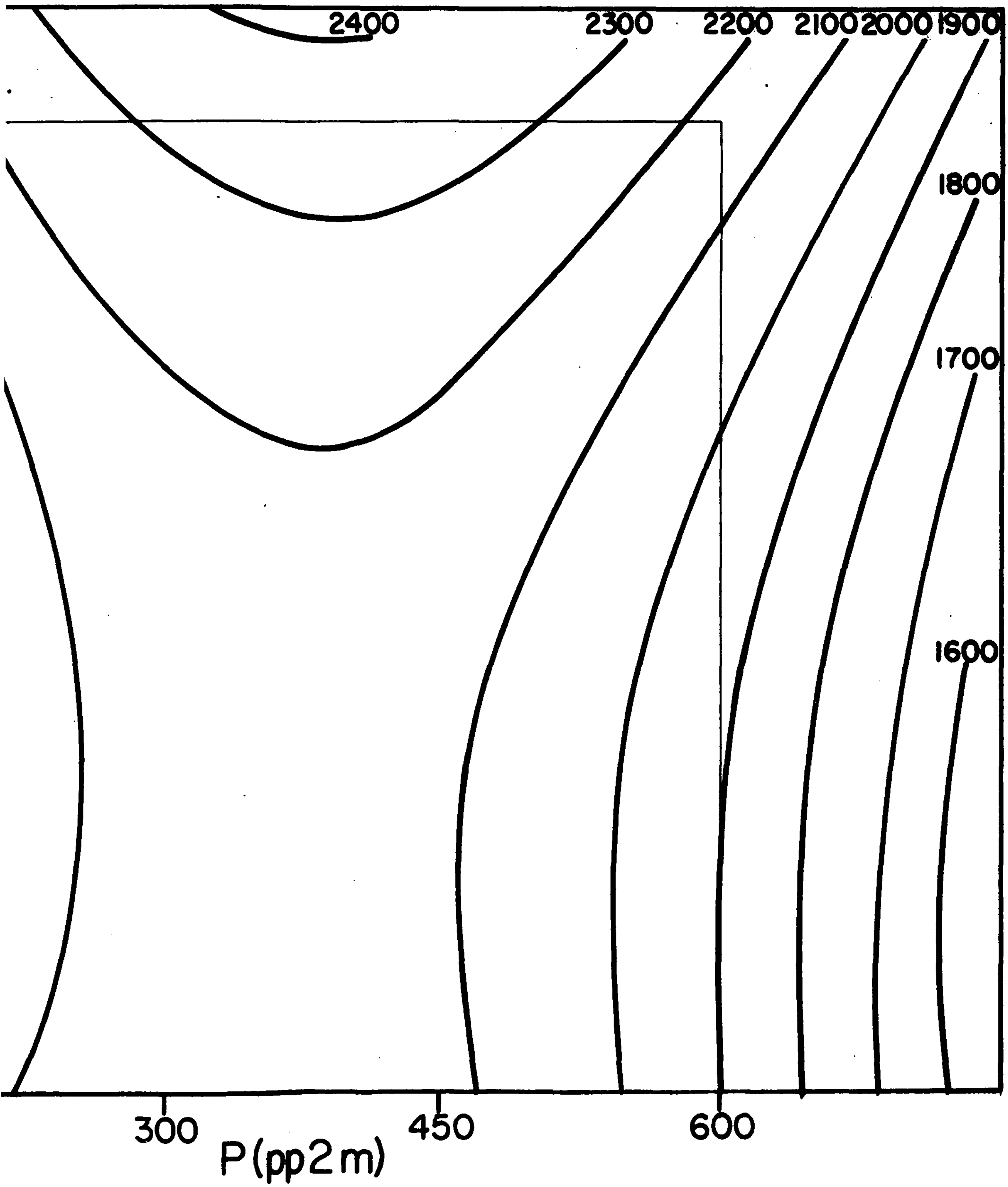
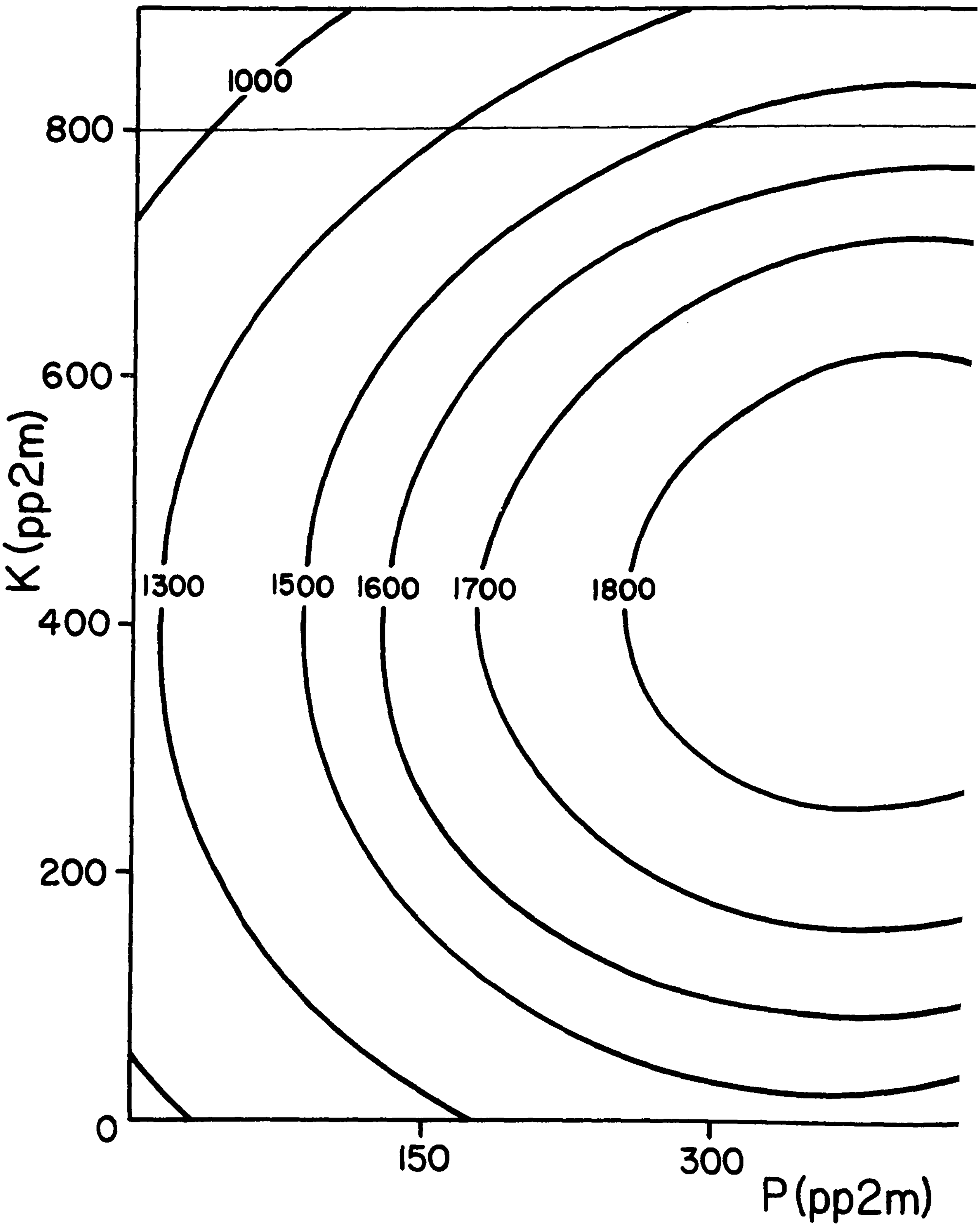
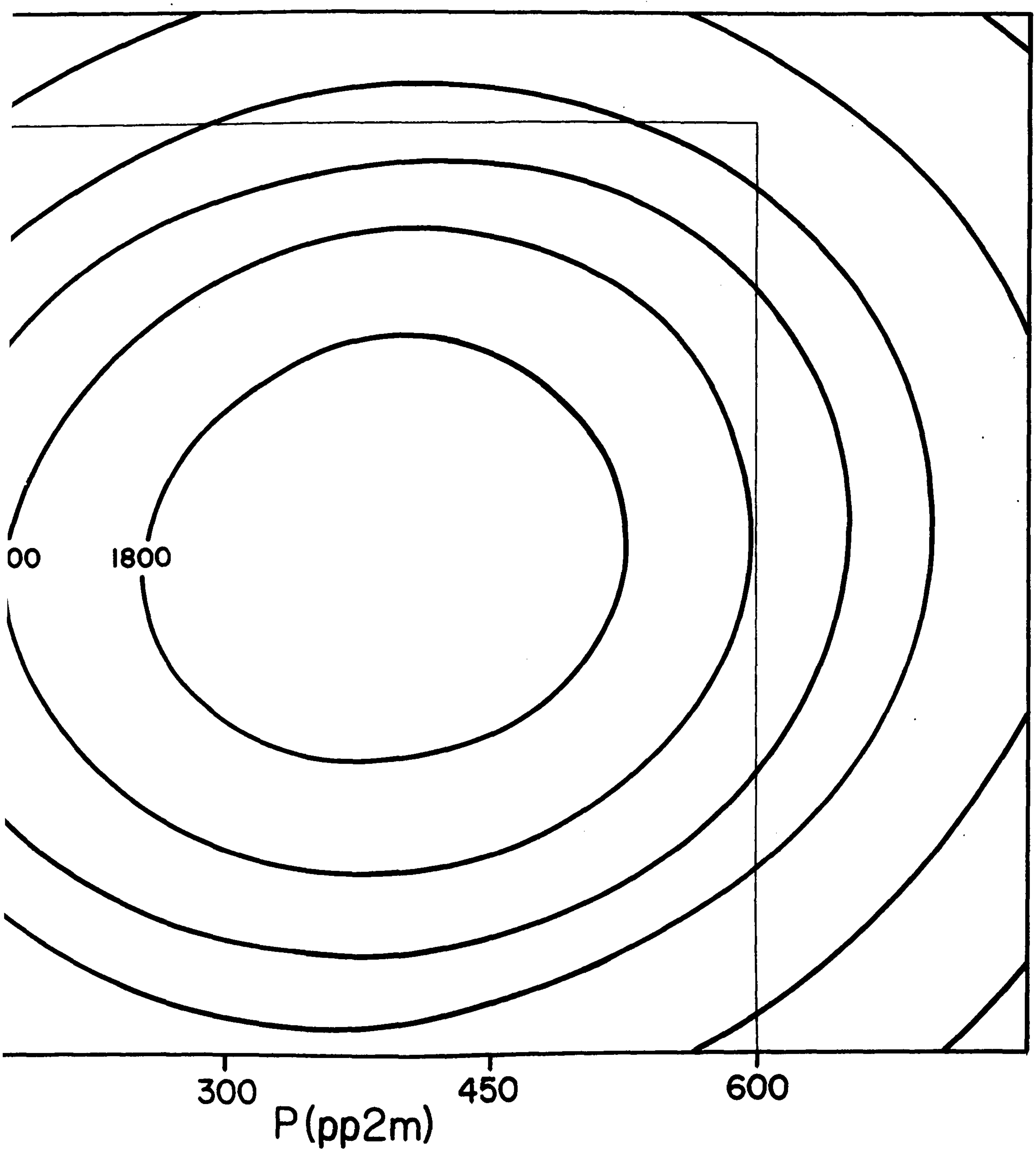

2400
2300
2200
2100
2000
1900
1800
1700
1600
300
450
600
P (pp2m)

Figure 36. Isoquants of number of nodules at the end of flowering for Entry 3, grown in pots in 1963, as a function of P and K, holding Ca constant at 2000 pp2m

——————— Limits of investigated area


1000
800
600
400
200
0
K (pp2m)
1300
1500
1600
1700
1800
150
300
P (pp2m)



00
1800
300
450
600
P (pp2m)

At the seven-leafed stage the various differential effects resulted in intersecting surfaces. Figures 39 and 40 illustrate that the fresh weight of the nodules of Entry 3 exceeded that of Entry 1 up to a rate of 375 pp2m P and that of Entry 2 over the entire area investigated.

The magnitude of predicted responses determined over the same range of fertilizer input as in previous sections is given in Table 111. The responses to 300 pp2m P were substantial and of the order of 100% of the weight of nodules. Differential responses, were also relatively large.

Optimum nodulation required large amounts of P and K (Table 112). The P level for maximum number and weight of nodules at the end of flowering for lines 1 and 2 corresponded closely to that required for maximum yield of grain.

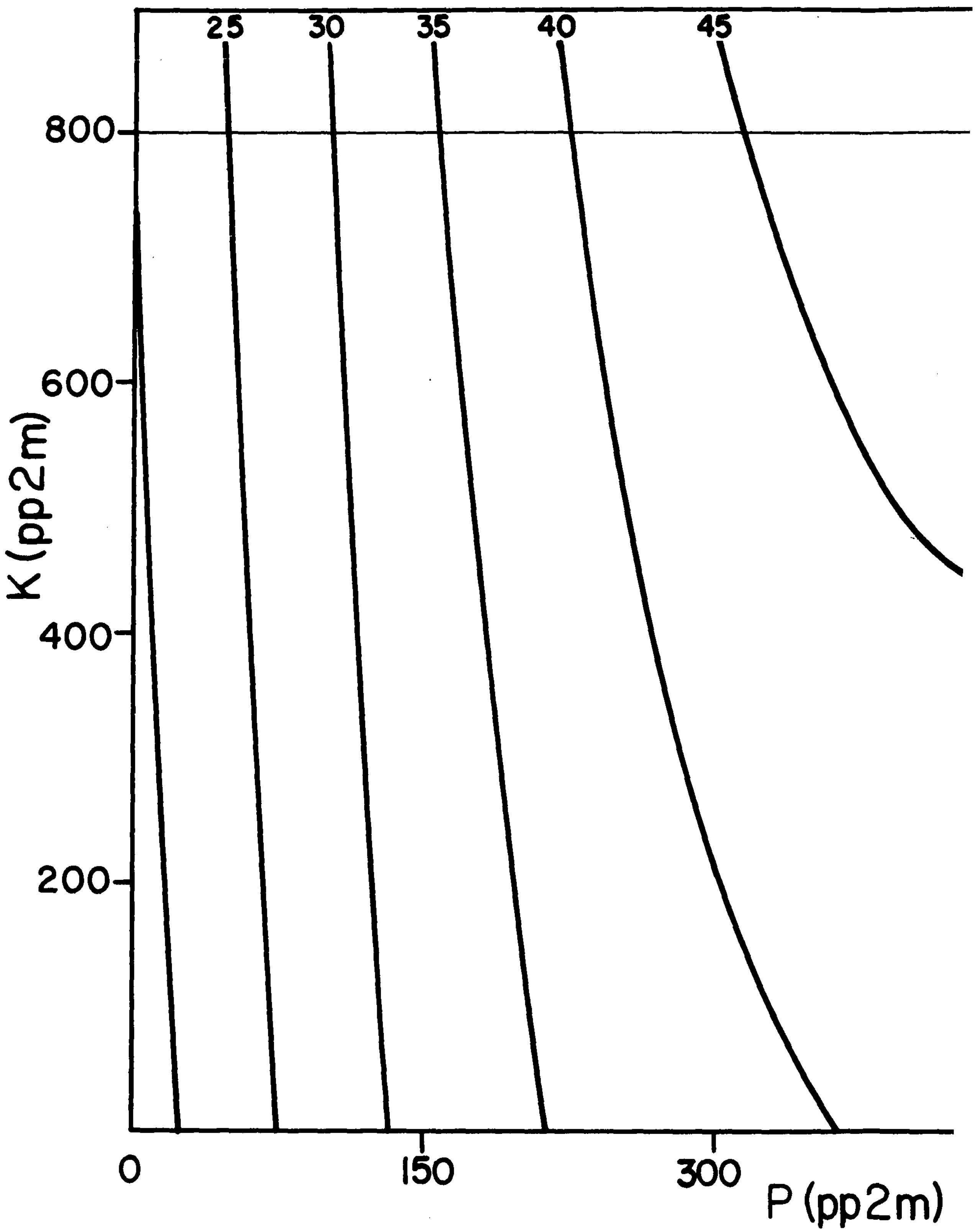
A three-fold increase in weight of nodules was predicted from fertilization which is approximately twice as much as that for the number of nodules and which corresponds to the maximum response in yield of grain (see Table 99).

The values recorded in Table 112 under the heading "$\hat{Y}_{max}$" also show that the maximum number of nodules attainable will increase two- to three-fold between the seven-leafed stage and the end of flowering. The weight of nodules may increase even more strongly over this period.

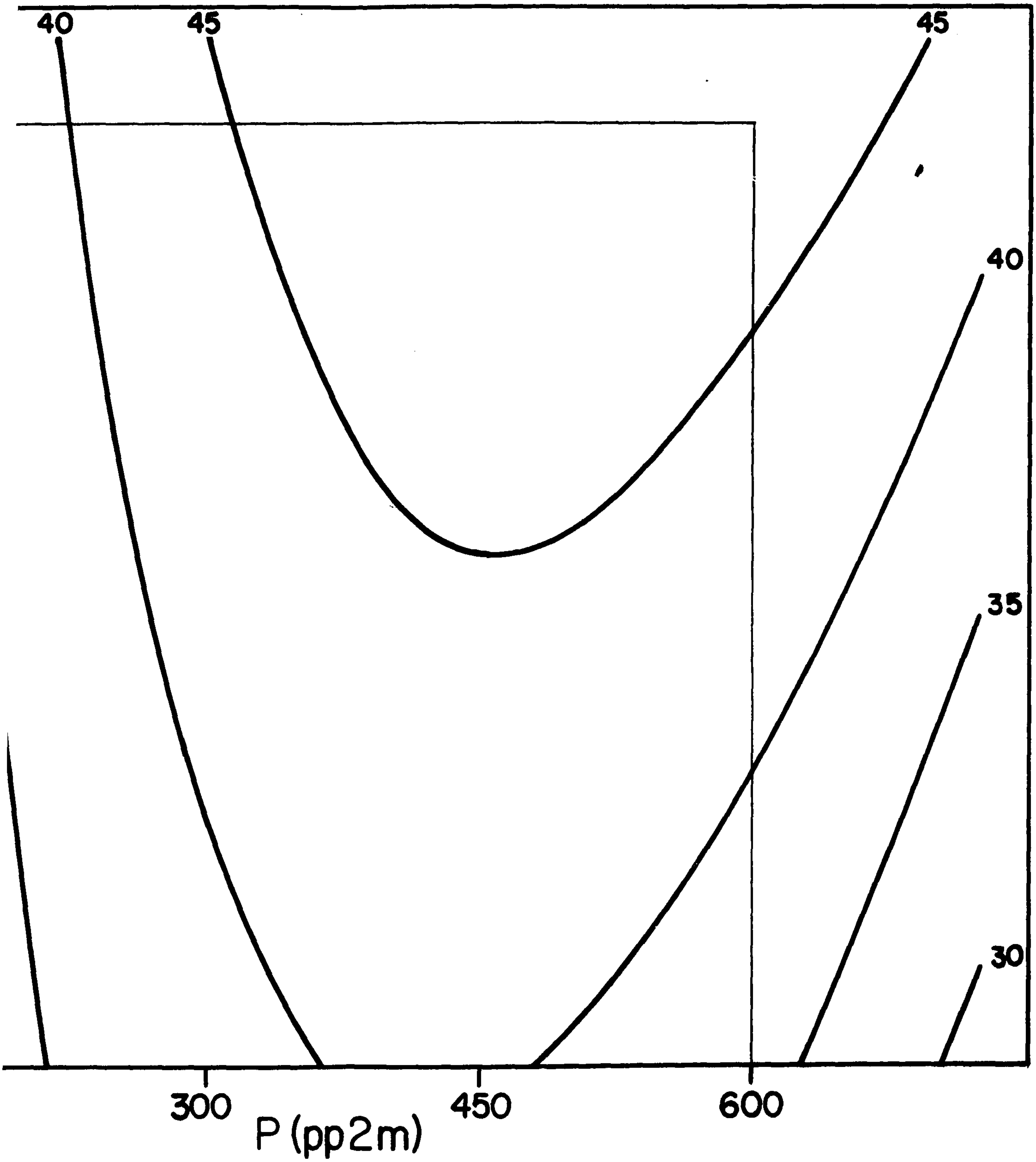
c. <u>Date of attainment of certain stages of development</u> The day of the month in July upon which the plants reached the seven-leafed stage was used as dependent value in the regressions. The date of the end of flowering was coded from July 29. For the date of maturity the day of the month in September was used.

Figure 37. Isoquants of nodule fresh-weight at the end of flowering for Entry 1 in 1963, expressed in grams per pot, as a function of P and K, holding Ca constant at 2000 pp2m

——————— Limits of investigated area



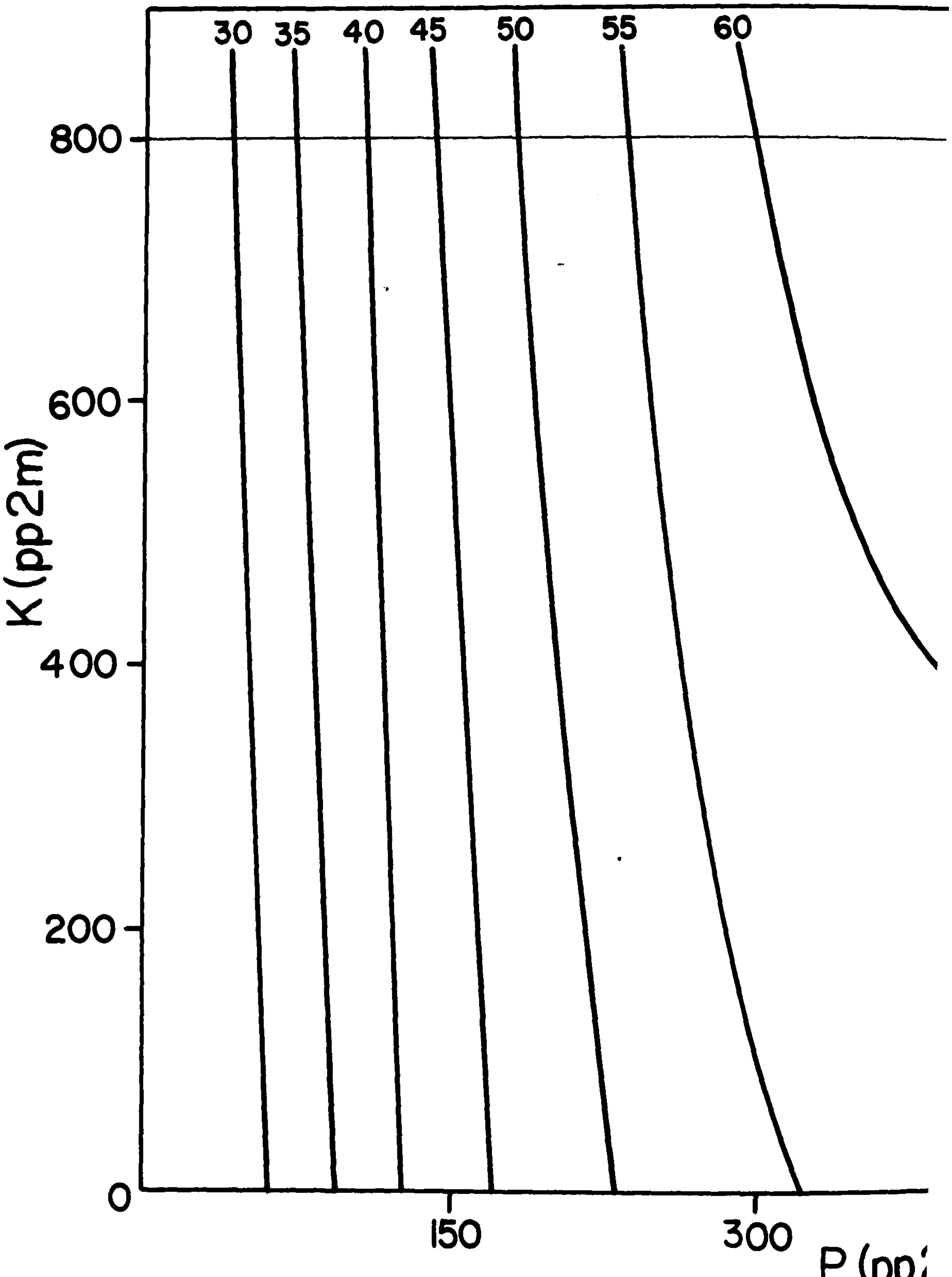
25
30
35
40
45
800
600
400
200
K (pp2m)
0
150
300
P (pp2m)



40
45
45
40
35
30
300
450
600
P (pp2m)

Figure 38. Isoquants of nodule fresh-weight at the end of flowering for Entry 2 in 1963, expressed in grams per pot, as a function of P and K, holding Ca constant at 2000 pp2m

——————— Limits of investigated area



30
35
40
45
50
55
60
800
600
400
200
0
K (pp2m)
150
300
P (pp2

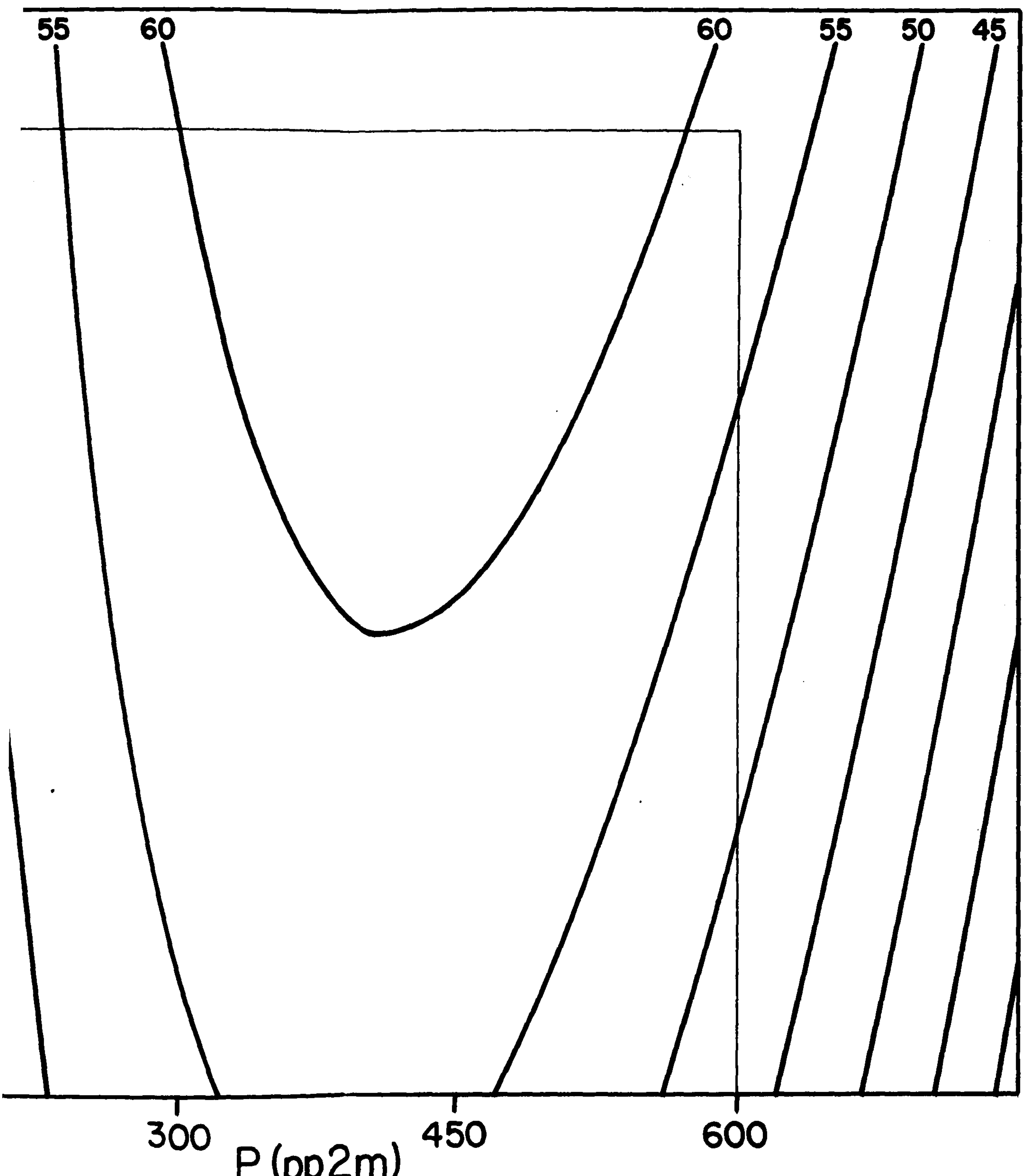
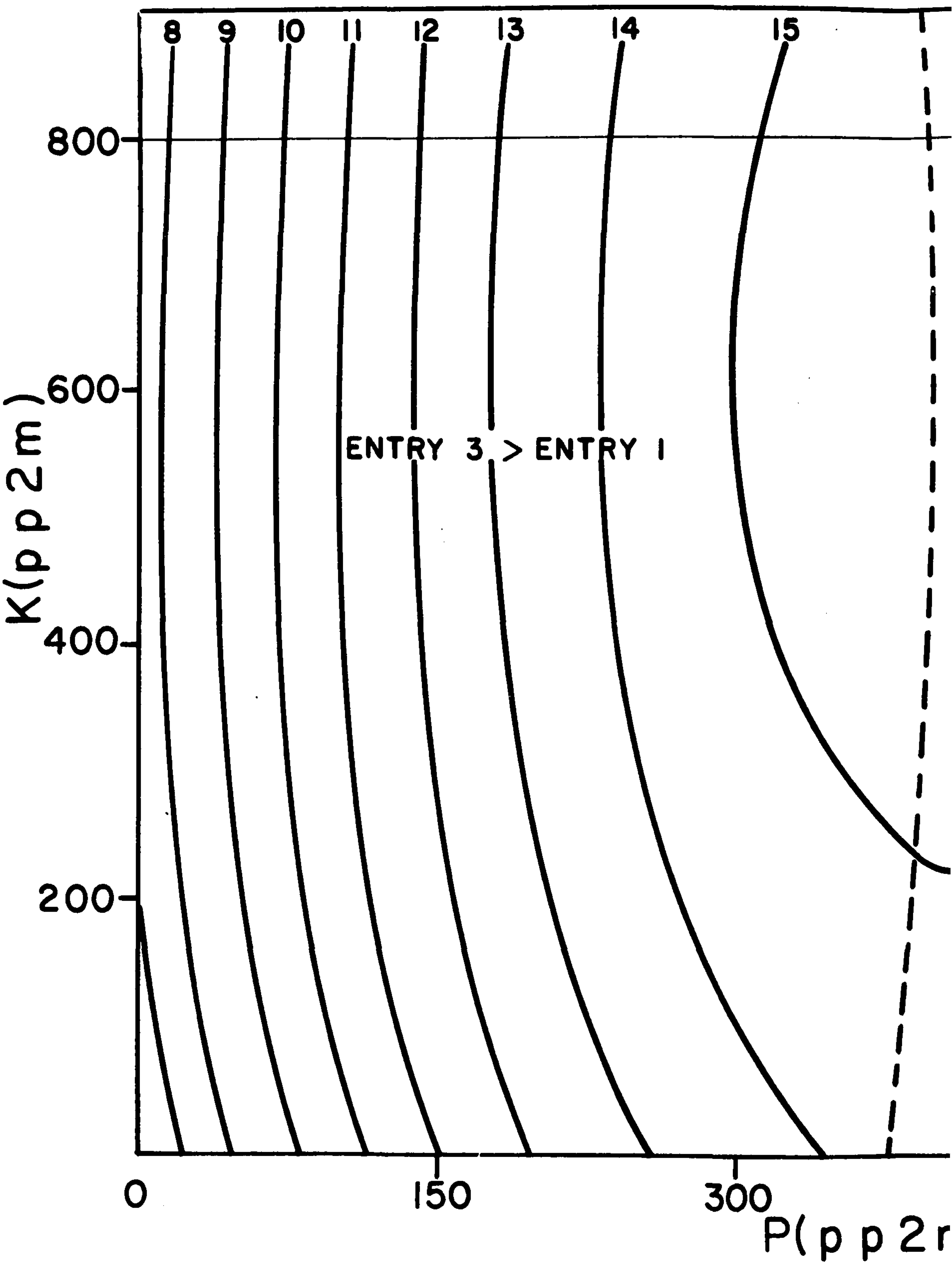

55
60
60
55
50
45
300
450
600
P (pp2m)

Figure 39. Isoquants of nodule fresh weight at the seven-leafed stage for Entry 1 in 1963, expressed in grams per pot, as a function of P and K, holding Ca constant at 2000 pp2m and the projection of the line of intersection between the surfaces for Entries 1 and 3

▬▬▬▬▬	Isoquants
▬ ▬ ▬ ▬	Projected line of intersection
─────	Limits of investigated area


8
9
10
11
12
13
14
15
800
600
400
200
K(pp2m)
ENTRY 3 > ENTRY 1
0
150
300

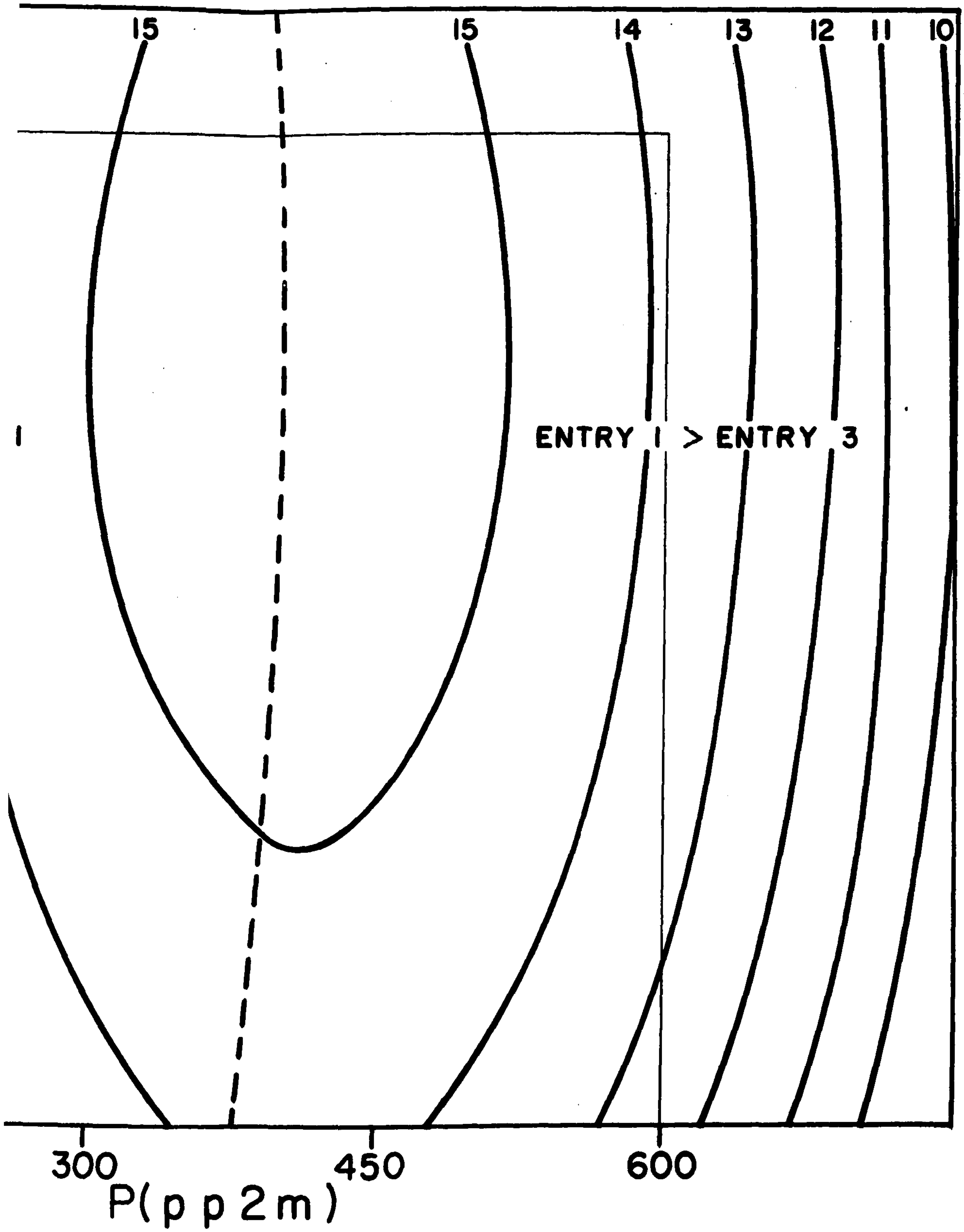
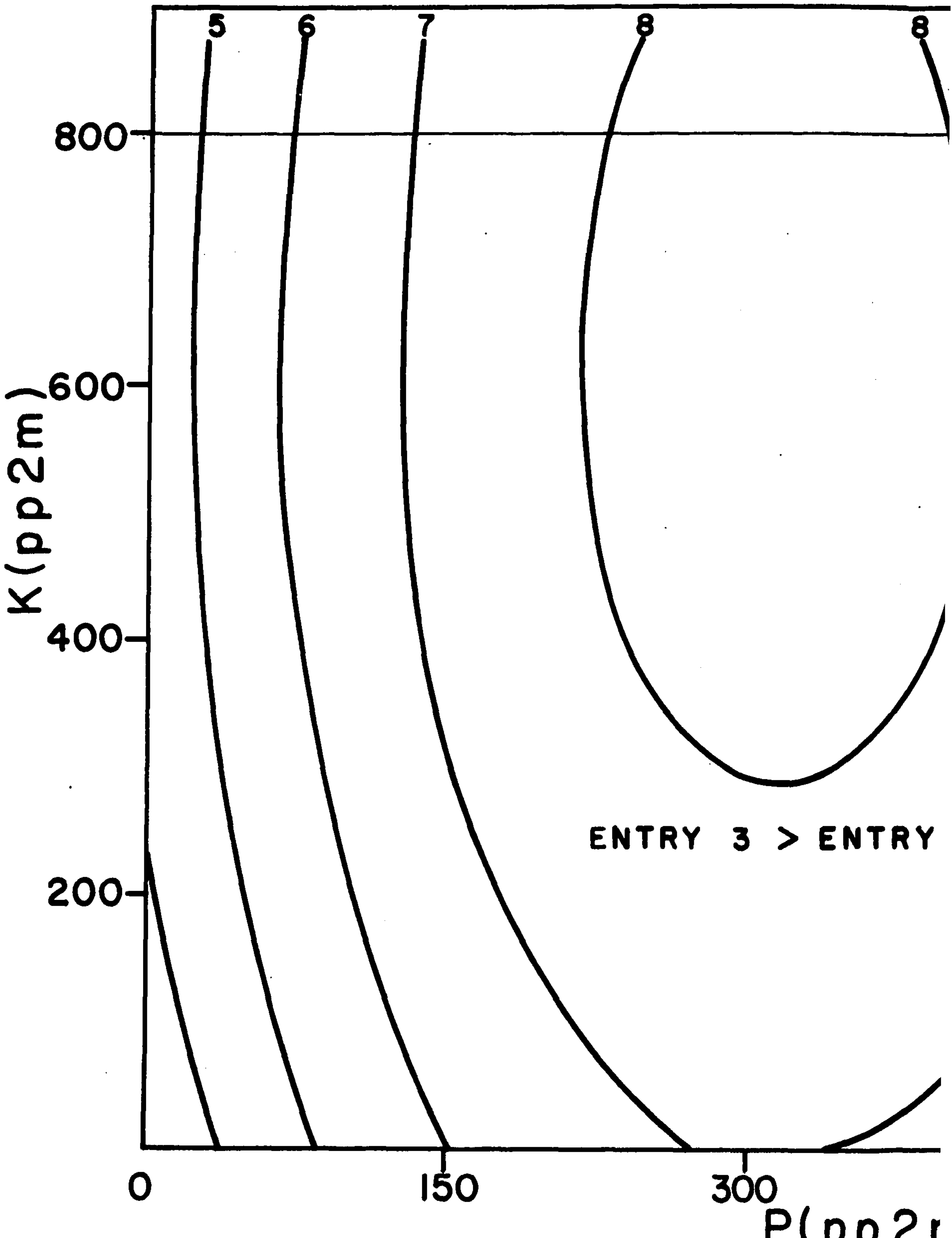

15
15
14
13
12
11
10
ENTRY 1 > ENTRY 3
300
450
600
P(pp2m)

Figure 40. Isoquants of nodule fresh weight at the seven-leafed stage for Entry 2 in 1963, expressed in grams per pot, as a function of P and K, holding Ca constant at 2000 pp2m acre; and the projection of the line of intersection between the surfaces for Entries 2 and 3

———	Isoquants
— — — —	Projected line of intersection
———	Limits of investigated area


5
6
7
8
8
800
600
400
200
K(pp2m)
ENTRY 3 > ENTRY
0
150
300
P(pp2r

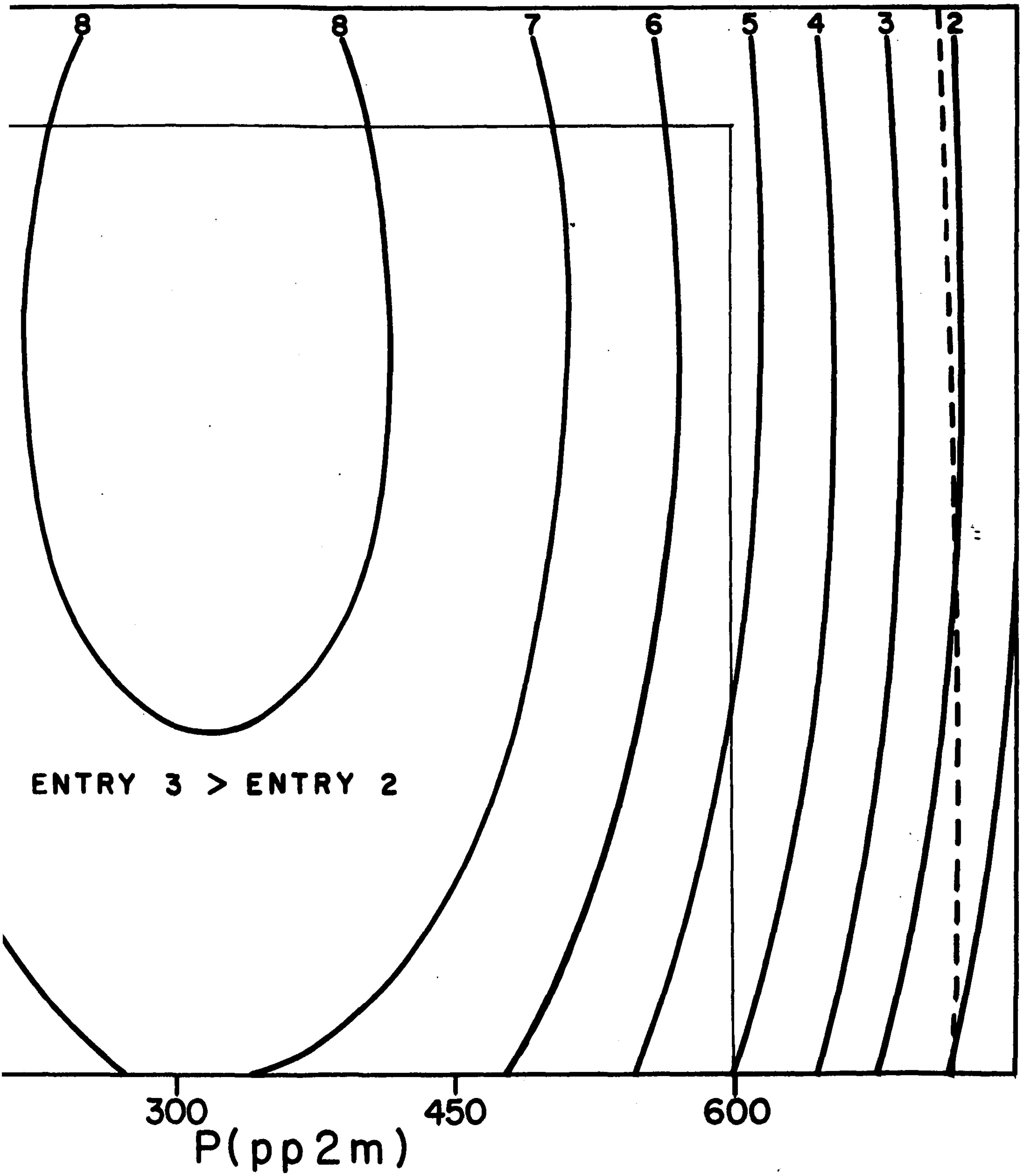

8
8
7
6
5
4
3
2
ENTRY 3 > ENTRY 2
300
450
600
P(pp2m)

Table 111. Magnitude of predicted responses and differential responses to P and K for the number and fresh weight of nodules at two stages of growth in 1963 involving one or more significant effects

Dependent variable	Stage of growth	Entry	Factor specification (pp2m)			Responses			Differential response
			P	K	Ca	from	to	response	
Number of nodules	End of flowering	1	0-300	400	2000	1600	2125	525	
		2	0-300	400	2000	1350	1940	590	
		3	0-300	400	2000	1250	1830	580	
		1	300	0-400	2000	2100	2100	0	
		3	300	0-400	2000	1400	1830	430	430
	Seven-leafed	1	0-300	400	2000	850	1137	287	
		2	0-300	400	2000	375	675	300	
Fresh weight of nodules (gms.)	End of flowering	1	0-300	400	2000	19	41	22	
		2	0-300	400	2000	22	57	35	13
	Seven-leafed	1	0-300	400	2000	7.5	14.7	7.2	
		2	0-300	400	2000	4.3	8.2	3.9	
		3	0-300	400	2000	8.0	15.7	7.7	3.8

Table 112. Fertilizer combination at maximum, maximum number and fresh weight of nodules and ratio of predicted number and fresh weight of nodules at the maximum and at no fertilization for three soybean lines, grown in pots in 1963 and harvested at two stages of development

Dependent variable	Stage of variable	Entry	Combination at maximum			$\hat{Y}_{max}$	$\hat{Y}_{max}/\hat{Y}_{check}$
			P	K	Ca		
Number of nodules	End of flowering	1	465	800	4000	2670	1.69
		2	495	500	3700	2020	1.56
		3	435	420	4000	2070	2.15
	Seven-leafed	1	360	800[a]	2800	1250	1.60
		2	353	800[a]	1900	670	2.14
Fresh weight nodules	End of flowering	1	480	590	1700	48	3.52
		2	473	800	0	74	3.02
	Seven-leafed	1	473	620	4000	17	2.37
		2	330	620	2200	9	2.21

[a]Maximum almost independent of the rate of K application.

The values obtained for attainment of each stage of development were employed as dependent variable in multiple regressions on fertilizer input variables.

F-tests on the overall regression indicated significance at the 0.01 level for the effect of fertilization on the dates of attainment of the seven-leafed stage and the end of flowering. The maturity date was not influenced significantly by fertilization. The F-values on the overall regression for maturity date of the three lines were 2.13, 0.69 and 5.33 for Entries 1, 2 and 3 respectively. None of the individual effects reached the 0.05 level of significance.

Analysis of the regression shows that P was the main factor affecting the date on which the seven-leafed stage and the end of flowering were reached. The end of flowering of Entry 2 was not affected by P, but rather by Ca application at the 0.05 level of significance (Table 113). These differences with the other lines caused a highly significant differencial effect due to P among the three lines and another at the 0.10 level of significance with respect to Ca. At the seven-leafed stage Entry 3 responded to several interaction terms and this also resulted in significant differential effects among the three soybean lines. Contour maps drawn for Entry 1 from the original equations showed that the seven-leafed stage depended strongly on P application. An application of 300 pp2m P delayed the seven-leafed stage by 4.5 days. This effect was practically independent of the rate of K applied. The end of flowering of Entry 1 and Entry 3 was affected by P application at the 0.01 level of significance. Entry 1 responded also to K but at a lower level of significance. Other less pronounced effects are indicated in Table 113. Both P and K had a negative effect on the maturity date. A contour map for Entry 1 showed a maximum delay of 3.5 days in the end of flowering at a combination of 420 pp2m P and 560 pp2m K when the Ca supply was held at 2000 pp2m.

4. Leaf composition at three stages of development as a function of fertilizer input variables

A. Leaf composition at the end of flowering   F-tests on the overall regression for each of the nutrients and varieties were all

Table 113. Partial regression coefficients relating the date of attainment of the seven-leafed stage, the end of flowering stage and maturity of three soybean lines, grown in pots in 1963, to fertilization; their significance and significant differential effects between lines

Dependent variable	Factor	Entry 1	Entry 2	Entry 3	Mean squares	F
Date of seven-leafed stage	b_o	14.0954**	8.0975	11.2248**	21.0345	20.60**
	P	-3.4797**	-2.7913**	-3.1101**	0.4590	< 1
	K	0.1273	-0.5643	-0.6459	0.7458	< 1
	Ca	-0.6849	0.5290	0.1502	1.6024	1.57+
	P^2	0.6225**	0.4265**	0.3904*	1.3497	1.32
	K^2	-0.0039	0.0457	0.1275	0.3792	< 1
	Ca^2	0.1838+	-0.2053+	0.0027	3.2649	3.20*
	PK	0.0105	0.0974	0.3477**	3.6196	3.55*
	PCa	-0.0334	0.0875	0.1824+	1.4445	1.42
	KCa	-0.0215	0.1882+	0.1831+	1.9054	1.87+
	PKCa	-0.0003	-0.0574+	-0.1503**	5.9807	5.86**
	R^2	0.7494	0.6580	0.7486		
	Experimental error				1.0211	
Date end of flowering	b_o	3.4305**	15.6670**	2.8137**	122.8372	129.20**
	P	-1.5063**	-0.7621	-0.8156*	6.4667	6.80**
	K	-0.7521+	-0.6366	-0.2466	0.2900	< 1
	Ca	0.1225	-1.3490*	-0.5690+	2.2514	2.37++
	P^2	0.2931**	0.1070	0.2139**	0.7545	< 1
	K^2	0.1641++	0.1026	0.0921	0.1303	< 1
	Ca^2	0.0394	0.2278+	0.0920	0.8139	< 1
	PK	-0.0180	0.0758	-0.1136+	1.1941	1.26

Table 113. (Continued)

Dependent variable	Factor	Entry 1	Entry 2	Entry 3	Mean squares	F
	PCa	-0.0333	0.0505	0.0263	0.2297	< 1
	KCa	-0.0391	0.1311+	0.0029	0.8739	< 1
	PKCa	-0.0044	-0.0565+	-0.0033	0.9645	1.01
	R^2	0.7143	0.4448	0.5786		
	Experimental error				0.9508	
Maturity date	b_o	16.5109**	18.2568**	11.7948**	26.5162	5.79**
	P	-1.5060+	-1.3915+	1.3847	10.3614	2.26+
	K	0.4685	-0.3207	0.8311	1.4335	< 1
	Ca	-0.3242	0.2724	2.0401++	6.2800	1.37
	P^2	0.3722+	0.2269	0.2727	0.4776	< 1
	K^2	-0.0178	-0.0884	0.4586++	7.6238	1.67+
	Ca^2	0.1698	-0.0891	0.3956+	5.0662	1.11
	PK	0.1017	0.3006+	0.1072	1.5155	< 1
	PCa	-0.2056	0.0199	0.1695	4.4023	< 1
	KCa	-0.0789	0.0073	0.2641+	4.2391	< 1
	PKCa	0.0267	-0.0165	0.0604	1.5504	< 1
	R^2	0.3783	0.1643	0.6036		
	Experimental error				4.57836	

highly significant. The F-values ranged from 10 to 174. The highest F-values were associated with the percent P in the leaves. In the regressions of the percent P on factors of fertilization significance at the 0.05 or 0.01 level was reached with respect to P, Ca^2, PK and PCa for all varieties (Table 114). The percent P of Entry 3 was also affected by K and K^2 at the 0.10 and 0.05 level of significance respectively. The percent K was affected to the 0.05 or 0.01 level by K and K^2 and in Entries 1 and 2 the percent K was affected also by Ca and Ca^2. The percent Ca of all varieties was mainly influenced by the linear and quadratic effects of P and K and their interaction; in most cases to the 0.01 level of significance. In Entries 2 and 3 the percent Ca also was affected significantly by Ca and Ca^2 effects. The percent Mg in Entry 3 responded to all three elements, their squares and the PCa interaction with significance at the 0.01 level. The percent Mg in the other two lines was affected mainly by P and K, their squares and interaction. The percent N responded most strongly to P and P^2. The partial regression coefficients reached the 0.01 level of significance in most cases. Entries 1 and 2 also responded to K, K^2 and to the PCa interaction at the 0.05 level of significance. The Ca^2 effect reached a lower level of significance.

Differential effects at the end of flowering were convincingly indicated by several highly significant F-values. The P, K, P^2, K^2, PCa and PKCa effects caused responses in percent P amongst the three varieties which differed at the 0.01 or 0.05 level of significance. Differential responses of the percent K in the leaves were due to the PCa effect at

Table 114. Partial regression coefficients relating the percentage composition of the leaves of three soybean lines grown in pots in 1963 and harvested at the end of flowering to fertilization; their level of significance and significant differential effects between lines

Dependent variable	Factor	Entry 1	Entry 2	Entry 3	Mean squares	F
%P	b_o	0.1704**	0.1252**	0.1583*	0.0013	< 1
	P	0.2394**	0.1822**	0.2709**	0.0078	4.61*
	K	-0.0168	-0.0183	-0.0879++	0.0068	4.01*
	Ca	-0.0496*	-0.0285	-0.0761+	0.0024	1.39
	P^2	0.0039	0.0034	0.0195++	0.0072	4.24*
	K^2	0.0046	0.0064+	0.0233*	0.0091	5.37**
	Ca^2	0.0133**	0.0102*	0.0232*	0.0040	2.34+
	PK	-0.0159**	-0.0260**	-0.0249**	0.0036	2.12+
	PCa	-0.0239**	-0.0294**	-0.0496**	0.0225	13.26**
	KCa	0.0007	-0.0018	0.0012	0.0004	< 1
	PKCa	0.0003	0.0056**	0.0018	0.0078	4.61*
	R^2	0.9803	0.9460	0.9376		
	Experimental error				0.00170	
%K	b_o	1.4009**	1.2362**	1.5340**	0.0503	2.09+
	P	-0.1645**	-0.0586	-0.0118	0.0217	< 1
	K	0.5614**	0.4174**	0.4760**	0.0217	< 1
	Ca	-0.1070*	-0.1589*	-0.2105+	0.0111	< 1
	P^2	0.0292*	-0.0064	0.0505+	0.0716	2.98++
	K^2	-0.0818**	-0.0676**	-0.0831*	0.0064	< 1

Table 114. (Continued)

Dependent variable	Factor	Entry 1	Entry 2	Entry 3	Mean squares	F
	Ca^2	0.0195++	0.0368*	0.0400	0.0105	< 1
	PK	0.0383**	0.0238+	0.0151	0.0162	< 1
	PCa	-0.0185++	-0.0173	-0.0656*	0.0939	3.91*
	KCa	-0.0017	0.0129	0.0169	0.0126	< 1
	PKCa	0.0039	0.0015	0.0070	0.0080	< 1
	R^2	0.9700	0.8816	0.7622		
	Experimental error				0.02403	
%Ca	b_o	1.5047**	1.5653**	1.1601**	0.1117	7.60**
	P	0.2800**	0.2847**	0.2968**	0.0003	< 1
	K	-0.2090**	-0.2621**	-0.1500*	0.0172	1.17
	Ca	0.0514	0.1762*	0.1538*	0.0184	1.25
	P^2	-0.0420**	-0.0321++	-0.0577**	0.0144	< 1
	K^2	0.0440**	0.0452**	0.0326*	0.0041	< 1
	Ca^2	-0.0016	-0.0311++	-0.0224+	0.0199	1.35
	PK	-0.0294**	-0.0313*	-0.0274*	0.0004	< 1
	PCa	-0.0014	-0.0130	0.0064	0.0118	< 1
	KCa	-0.0046	-0.0059	-0.0091	0.0007	< 1
	PKCa	-0.0004	0.0045	0.0015	0.0063	< 1
	R^2	0.8599	0.7966	0.7492		
	Experimental error				0.01470	

Table 114. (Continued)

Dependent variable	Factor	Entry 1	Entry 2	Entry 3	Mean squares	F
%Mg	b_o	0.4495**	0.5055**	0.3628**	0.0121	5.73**
	P	0.0910**	0.0827*	0.0625**	0.0008	< 1
	K	-0.0881	-0.1428**	-0.1282**	0.0033	1.57+
	Ca	0.0251	0.0542++	0.0671	0.0017	< 1
	P^2	-0.0139*	-0.0105+	-0.0155**	0.0006	< 1
	K^2	0.0274**	0.0307**	0.0276**	0.0003	< 1
	Ca^2	-0.0032	-0.0108+	-0.0139**	0.0026	1.24
	PK	-0.0206**	-0.0155**	-0.0023	0.0105	5.00**
	PCa	0.0048	-0.0012	0.0124**	0.0057	2.70++
	KCa	-0.0145**	-0.0050	-0.0044	0.0043	2.05+
	PKCa	0.0018	0.0009	-0.0021+	0.0041	1.95+
	R^2	0.7809	0.7839	0.8342		
	Experimental error				0.00211	
%N	b_o	2.9691**	2.9136**	2.9219**	0.0021	< 1
	P	1.2307**	0.7640**	0.8486**	0.2391	4.12*
	K	0.2999*	0.2740*	0.1557	0.0244	< 1
	Ca	-0.0941	-0.0604	-0.0672	0.0013	< 1
	P^2	-0.1754**	-0.1012**	-0.0909*	0.1839	3.15*
	K^2	-0.0644*	-0.0607*	-0.0309	0.0035	< 1
	Ca^2	0.0424+	0.0405++	0.0305	0.0035	< 1
	PK	-0.0189	0.0113	0.0158	0.0420	< 1

Table 114. (Continued)

Dependent variable	Factor	Entry 1	Entry 2	Entry 3	Mean squares	F
	PCa	-0.0717**	-0.0468*	-0.0394+	0.0354	< 1
	KCa	-0.0008	-0.0097	0.0466++	0.1219	2.09+
	PKCa	0.0099+	0.0010	-0.0130+	0.1387	2.38+
	R^2	0.9115	0.8740	0.8336		
	Experimental error				0.05831	

the 0.05 level and the P^2 effect at the 0.10 level of significance. The percent Mg was differentially affected by the PK interaction at the 0.01 level and the PCa interaction effect at the 0.10 level of significance, while there were also highly significant varietal differences when no fertilizer was applied. Differential effects in percent N were mainly due to P and P^2 which were also the major factors controlling the N content of the plant. Several weaker suggestions at the 0.25 level of significance also existed for each of the nutrients mentioned (Table 114).

The combined equations show a higher level of significance for those terms which already were significant in the original regression equations. Several new terms gained significance (Table 115). In the combined equation for the percent P the PKCa effect for Entry 3 now reached significance. In the combined equation for the percent K the coefficient for P^2 of Entry 1 lost some significance, while that of Entry 3 gained some. The gains may be explained by the fact that the experimental error used to test the partial regression coefficients in the combined equations was smaller than the residual error from the regressions. A loss in significance for the coefficient of a particular variety may be caused by the readjustment of all other coefficients in the original equation for that variety when a new model is fitted to the combined data. A gain in the level of significance is more common than a loss under the conditions of these experiments.

Duncan's multiple range test substantiated and specified the result of Williams' F test in almost every case where the significance level was high. Where Williams' F test had shown weak suggestions of dif-

Table 115. Partial regression coefficients, b_i, of the combined equations for the chemical composition of the leaves at the end of flowering in 1963 for five elements; t-values and their significance

Dependent variable	Factor	b_i	t
%P	b_o	0.1513	9.78**
	V_1xP	0.2492	13.60**
	V_2xP	0.1817	9.92**
	V_3xP	0.2616	14.28**
	V_1xK	-0.0080	0.45
	V_2xK	-0.0205	1.16
	V_3xK	-0.0945	5.36**
	Ca	-0.0514	4.40**
	V_1xP^2	0.0030	0.71
	V_2xP^2	0.0024	0.56
	V_3xP^2	0.0214	5.10**
	V_1xK^2	0.0035	0.84
	V_2xK^2	0.0055	1.31+
	V_3xK^2	0.0252	6.01**
	V_1xCa^2	0.0147	5.30**
	V_2xCa^2	0.0139	5.03**
	V_3xCa^2	0.0180	6.50**
	V_1xPK	-0.0172	5.14**
	V_2xPK	-0.0244	7.30**
	V_3xPK	-0.0251	7.50**
	V_1xPCa	-0.0252	7.75**
	V_2xPCa	-0.0281	8.65**
	V_3xPCa	-0.0495	15.21**
	KCa	0.0000	0.08
	V_1xPKCa	0.0005	0.49
	V_2xPKCa	0.0051	4.97**
	V_3xPKCa	0.0021	2.02*
	R^2	0.9553	

Table 115. (Continued)

Dependent variable	Factor	b_i	t
%K	V_1	1.4514	25.78**
	V_2	1.1653	20.70**
	V_3	1.4453	25.68**
	P	-0.1006	2.30*
	K	0.5032	12.24**
	Ca	-0.1400	3.41**
	$V_1 x P^2$	0.0190	1.81+
	$V_2 x P^2$	-0.0059	0.57
	$V_3 x P^2$	0.0603	5.75**
	K^2	-0.0775	8.03**
	Ca^2	0.0321	3.33**
	PK	0.0369	6.80**
	$V_1 xPCa$	-0.0197	2.60*
	$V_2 xPCa$	-0.0064	0.85
	$V_3 xPCa$	-0.0504	6.65**
	R^2	0.8603	
%Ca	V_1	1.4859	38.35**
	V_2	1.5635	40.36**
	V_3	1.2503	32.27**
	P	0.2823	8.82**
	K	-0.2194	6.87**
	Ca	0.1133	3.55**
	P^2	-0.0440	5.87**
	K^2	0.0404	5.40**
	Ca^2	-0.0177	2.53*
	PK	-0.0255	6.01**
	R^2	0.7961	

Table 115. (Continued)

Dependent variable	Factor	b_i	<u>t</u>
%Mg	V_1	0.4499	21.24**
	V_2	0.5158	24.35**
	V_3	0.3521	16.62**
	P	0.0787	5.84**
	V_1xK	-0.0949	6.41**
	V_2xK	-0.1385	9.36**
	V_3xK	-0.1257	8.49**
	Ca	0.0488	3.75**
	P^2	-0.0133	4.67**
	K^2	0.0286	10.00**
	Ca^2	-0.0093	3.25**
	V_1xPK	-0.0188	5.56**
	V_2xPK	-0.0111	3.30**
	V_3xPK	-0.0084	2.49*
	V_1xPCa	0.0076	2.62*
	V_2xPCa	0.0013	0.46
	V_3xPCa	0.0071	2.47*
	V_1xKCa	-0.0145	4.57**
	V_2xKCa	-0.0055	1.74+
	V_3xKCa	-0.0039	1.24
	V_1xPKCa	0.0014	1.16
	V_2xPKCa	0.0002	0.20
	V_3xPKCa	-0.0011	0.87
	R^2	0.8152	

Table 115. (Continued)

Dependent variable	Factor	b_i	t
%N	b_o	2.9349	32.18**
	V_1xP	1.2273	13.80**
	V_2xP	0.8035	9.04**
	V_3xP	0.8126	9.14**
	K	0.2432	3.55**
	Ca	-0.0739	1.08
	V_1xP^2	-0.1859	8.72**
	V_2xP^2	-0.1050	4.92**
	V_3xP^2	-0.0765	3.59**
	K^2	-0.0520	3.46**
	Ca^2	0.0378	2.52*
	PK	0.0028	0.22
	PCa	-0.0526	4.20**
	V_1xKCa	0.0026	0.18
	V_2xKCa	-0.0050	0.34
	V_3xKCa	0.0384	2.67**
	V_1xPKCa	0.0025	0.47
	V_2xPKCa	0.0031	0.59
	V_3xPKCa	-0.0077	1.45+
	R^2	0.8755	

ferential effects these were sometimes not upheld by Duncan's test. Examples are the differential PK effects on the percent P and the PKCa effects on the percent Mg and percent N. It may be seen from Table 116 that the strongest and most significant differences occurred with respect to the P, P^2 and PCa effects. The difference of the PCa effect on the

Table 116. Comparison of corresponding partial regression coefficients in the combined equations for the chemical composition with respect to five elements in the leaves of three soybean lines at the end of flowering in 1963, using Duncan's multiple range test

Dependent variable	Nature of differential response	Line, regression coefficients and significance of differences[a]		
%P	P	2	1	3
		0.1817	0.2492	0.2616
	K	3	2	1
		-0.0945	-0.0205	-0.0080
	P^2	2	1	3
		0.0024	0.0030	0.0214
	K^2	1	2	3
		0.0035	0.0055	0.0252
	Ca^2	1	2	3
		0.0139	0.0147	0.0180
	PK	3	2	1
		-0.0251	-0.0244	-0.0172
	PCa	3	2	1
		-0.0495	-0.0281	-0.0252
	PKCa	2	3	1
		0.0051	0.0021	0.0005
%K	Variety	2	3	1
		1.1653	1.4453	1.4514
	P^2	2	1	3
		-0.0059	0.0190	0.0603
	PCa	3	1	2
		-0.0514	-0.0197	-0.0064

[a]Comparisons failing to reach the 0.05 level of significance are underlined with a solid line. In addition, those reaching the 0.05 level but not the 0.01 level of significance are indicated with a broken line.

Table 116. (Continued)

Dependent variable	Nature of differential response	Line, regression coefficients and significance of differences[a]		
%Ca	Variety	3 1.2503	1 1.4859	2 1.5635
%Mg	Variety	3 0.3521	1 0.4499	2 0.5158
	K	2 -0.1385	3 -0.1257	1 -0.0949
	PK	1 -0.0188	2 -0.0111	3 -0.0084
	PCa	2 0.0013	3 0.0071	1 0.0076
	KCa	1 -0.0145	2 -0.0055	3 -0.0039
	PKCa	3 -0.0011	2 0.0002	1 0.0014
%N	P	2 0.8035	3 0.8126	1 1.2273
	P^2	1 -0.1859	2 -0.1050	3 -0.0765
	KCa	2 -0.0050	1 0.0026	3 0.0384
	PKCa	3 -0.0077	1 0.0025	2 0.0031

percent P in the leaves of Entry 1 and Entry 3 was more than twice as large as required to reach the 0.01 level of significance. The same applied to the differential effect of P^2 on the percent K in the leaves of Entry 3 versus the other two lines. This indicated that the percent K in the leaves of Entry 3 was highly responsive to P. Entry 3 was selected for its high K content in the leaves in a previous field trial.

The PCa interaction effect on the percent K of Entry 3 was further much more strongly negative than for the other two lines. In connection with its high K content the percent Mg in the leaves of Entry 3 was relatively low. This is borne out by the difference in effect subscribed to varietal characteristics. Entry 3 was lower in Mg content by more than twice the minimum difference required for significance at the 0.01 level of probability. A comparably strong differential P effect occurred with respect to the percent N in the leaves of Entry 1 versus the other lines. The percent N of Entry 1 responded most strongly to P application. Entry 1 was selected for a high percent P in the leaves at the end of flowering.

b. Leaf composition at the seven-leafed stage F-tests on the overall effects of fertilization in the regression analysis were significant at the 0.01 level with the exception of that for the percent N of Entry 2 which reached the 0.05 level. The F-values were mostly higher than 10, especially where the percent P was the dependent variable.

Among the factors affecting the percent P were P, Ca^2 and PCa which also had a highly significant effect at the end of flowering. In addition, Ca and P^2 effects were more pronounced at this younger stage, while the

PK interaction was a less significant factor. The percent K was largely affected by K, K^2 and the PK or PCa interaction. All previously mentioned effects involving K were significant at the 0.01 level. The percent N was most strongly influenced by P and P^2 with partial regression coefficients reaching the 0.01 level of significance. The Ca, Ca^2 and PKCa effects were significant at the 0.05 level in Entry 1 (Table 117).

Differential effects at the seven-leafed stage were fewer in number and less significant than at the end of flowering. For the percent P the differential effects of P^2, PK, PCa and PKCa now reached only the 0.25 level of significance. The PK interaction was the only effect of significance at the 0.01 level which affected the percent K differentially. The KCa and PKCa interactions maintained their differential effect on the percent N at the 0.25 and 0.10 level of significance.

Combination of the regression equations and retention of individual estimates for the three lines where a suggestion of differential effects existed, resulted in the three equations shown in Table 118. The significance of the PK interaction effect for Entry 3 in the combined equation for the percent P was raised from the 0.20 to the 0.01 level of probability. The effect of P on the percent K in the leaves reached the 0.05 level of significance as an average effect for the three lines whereas the estimates for the individual soybean lines had no significance. No meaningful changes resulted from combining the data for the percent N in the leaves.

Duncan's multiple range test showed that differential responses in

Table 117. Partial regression coefficients relating the percentage composition of the leaves of three soybean lines grown in pots in 1963 and harvested at the seven-leafed stage, to fertilization; their level of significance and significant differential effects between lines

Dependent variable	Factor	Entry 1	Entry 2	Entry 3	Mean squares	F
%P	b_o	0.2857**	0.2428**	0.2942**	0.0018	< 1
	P	0.2438**	0.2193**	0.2826**	0.0039	< 1
	K	-0.0556	0.0590	-0.0145	0.0132	1.33
	Ca	-0.1158*	-0.1265*	-0.2074*	0.0104	1.05
	P^2	0.0215*	0.0533**	0.0391*	0.0219	2.22+
	K^2	0.0140	-0.0102	0.0051	0.0128	1.30
	Ca^2	0.0302**	0.0330**	0.0508**	0.0107	1.08
	PK	0.0019	-0.0218*	-0.0228+	0.0229	2.32+
	PCa	-0.0249**	-0.0554**	-0.0472**	0.0307	3.10+
	KCa	-0.0005	-0.0047	0.0011	0.0012	< 1
	PKCa	-0.0059*	0.0025	-0.0019	0.0180	1.82+
	R^2	0.9599	0.9656	0.9077		
	Experimental error				0.0099	
%K	b_o	1.9079**	1.9061**	1.8939**	0.0001	< 1
	P	-0.0143	-0.0006	0.0655	0.0070	< 1
	K	0.4961**	0.4014**	0.5881**	0.0360	1.68+
	Ca	-0.1535	-0.0673	-0.1324+	0.0084	< 1
	P^2	0.0075	0.0168	0.0050	0.0033	< 1
	K^2	-0.0952**	-0.0675**	-0.1085**	0.0376	1.75+
	Ca^2	0.0229	0.0130	0.0183	0.0021	< 1

Table 117. (Continued)

Dependent variable	Factor	Entry 1	Entry 2	Entry 3	Mean squares	F
	PK	0.0667**	0.0104	0.0103	0.1250	5.83**
	PCa	-0.0179	-0.0278++	-0.0311*	0.0058	< 1
	KCa	0.0055	-0.0069	0.0096	0.0098	< 1
	PKCa	-0.0036	0.0030	0.0078+	0.0343	1.60+
	R^2	0.8101	0.7789	0.9067		
	Experimental error				0.02145	
%N	b_o	3.8451**	3.5312**	3.7285**	0.0600	< 1
	P	0.5588**	0.6655**	0.6900**	0.0188	< 1
	K	-0.0907	-0.0308	0.0695	0.0271	< 1
	Ca	0.3132*	0.2523+	0.0359	0.0882	1.15
	P^2	-0.1029**	-0.1357**	-0.1490**	0.0487	< 1
	K^2	0.0250	0.0444	-0.0213	0.0982	1.28
	Ca^2	-0.0558*	-0.0500	-0.0157	0.0404	< 1
	PK	-0.0194	-0.0384	0.0244	0.1225	1.59
	PCa	-0.0237	-0.0194	0.0291+	0.1060	1.38
	KCa	-0.0369++	-0.0340	0.0241	0.1573	2.05+
	PKCa	0.0193*	0.0106	-0.0102+	0.1873	2.44++
	R^2	0.7037	0.4115	0.8009		
	Experimental error				0.07688	

Table 118. Partial regression coefficients, b_i, of the combined equations for the chemical composition of the leaves at the seven-leafed stage in 1963 for three elements; t-values and their significance

Dependent variable	Factor	b_i	t
%P	b_o	0.2725	7.29**
	P	0.2449	8.68**
	K	0.0082	0.60
	Ca	-0.1540	5.73**
	V_1xP^2	0.0231	3.44**
	V_2xP^2	0.0464	6.91**
	V_3xP^2	0.0475	7.07**
	Ca^2	0.0390	6.72**
	V_1xPK	-0.0008	0.11
	V_2xPK	-0.0184	2.59*
	V_3xPK	-0.0235	3.31**
	V_1xPCa	-0.0263	3.95**
	V_2xPCa	-0.0554	8.31**
	V_3xPCa	-0.0465	6.97**
	KCa	-0.0014	0.27
	V_1xPKCa	-0.0055	2.28*
	V_2xPKCa	0.0014	0.59
	V_3xPKCa	-0.0012	0.51
	R^2	0.9393	
%K	b_o	1.8804	34.39**
	P	0.0454	2.15*
	V_1xK	0.3851	8.16**
	V_2xK	0.3825	8.11**
	V_3xK	0.5436	11.52**
	Ca	-0.0467	2.35*
	V_1xK^2	-0.0670	5.95**

Table 118. (Continued)

Dependent variable	Factor	b_i	$\underline{t}$
	V_2xK^2	-0.0643	5.71**
	V_3xK^2	-0.0962	8.54**
	V_1xPK	0.0557	5.56**
	V_2xPK	0.0145	1.45+
	V_3xPK	0.0171	1.71++
	PCa	-0.0209	2.86**
	KCa	0.0027	0.38
	V_1xPKCa	-0.0017	0.56
	V_2xPKCa	0.0019	0.59
	V_3xPKCa	0.0071	2.26*
	R^2	0.8273	
%N	b_o	3.6921	35.43**
	P	0.6184	7.87**
	K	0.0469	1.24
	Ca	0.1782	2.38*
	P^2	-0.1235	7.67**
	Ca^2	-0.0350	2.16*
	PK	-0.0111	0.76
	PCa	-0.0059	0.41
	V_1xKCa	-0.0225	1.39+
	V_2xKCa	-0.0217	1.34+
	V_3xKCa	-0.0026	0.16
	V_1xPKCa	0.0135	2.31*
	V_2xPKCa	-0.0007	0.13
	V_3xPKCa	0.0070	1.19
	R^2	0.5598	

Table 119. Comparison of corresponding partial regression coefficients in the combined equations for the chemical composition with respect to three elements in the leaves of three soybean lines at the stage of seven trifoliate leaves in 1963, using Duncan's multiple range test

Independent variable	Nature of differential response	Line, regression coefficients, and significance of differences[a]		
%P	P^2	1	2	3
		0.0231	0.0464	0.0475
	PK	3	2	1
		-0.0235	-0.0184	-0.0008
	PCa	2	3	1
		-0.0554	-0.0465	-0.0263
	PKCa	1	3	2
		-0.0055	-0.0012	0.0014
%K	K	2	1	3
		0.3825	0.3851	0.5436
	K^2	3	1	2
		-0.0962	-0.0670	-0.0643
	PK	2	3	1
		0.0145	0.0171	0.0557
	PKCa	1	2	3
		-0.0017	0.0019	0.0071
%N	KCa	1	2	3
		-0.0225	-0.0217	-0.0026
	PKCa	2	3	1
		-0.0007	0.0070	0.0135

[a]Comparisons failing to reach the 0.05 level of significance are underlined with a solid line. In addition, those reaching the 0.05 level but not the 0.01 level of significance are indicated with a broken line.

percent P of the leaves due to P^2 and PCa already existed at the seven-leafed stage (Table 119). Highly significant differential responses also existed at this stage. They were due mainly to K and PK while the P^2 and PCa effects caused very strong differences at the end of flowering. Hardly any differential responses were found for the percent N in the leaves.

c. <u>Leaf composition at the two-leafed stage</u> F-tests on the overall regression were again highly significant with F-values up to 150 for the percent P and low values for the percent N. The regression for the percent N of Entry 1 only reached the 0.05 level.

The variation in percent P could be largely explained by the highly significant effects from P and Ca, their squares and interaction all of which reached the 0.01 level of significance for all lines. The K and K^2 effects reached the 0.05 level for Entries 1 and 3 and the 0.20 level of significance for Entry 2. The percent K was affected to a high degree of significance by K and K^2 and by the PK interaction to lower levels of significance for all lines. Ca and Ca^2 were also consistently involved with high significance in Entries 2 and 3 and at the 0.20 level in Entry 1. The percent N was only influenced weakly by Ca and Ca^2 to various levels of significance in the three lines (Table 120).

Hardly any differential effects existed at this early stage. The PCa interaction was the only differential effect on the percent P and reached only the 0.25 level. For the percentages K and N it was the linear and quadratic components of Ca and K respectively which offered a weak suggestion of differential effects at the two-leafed stage.

Table 120. Partial regression coefficients relating the percentage composition of the leaves of three soybean lines grown in pots in 1963 and harvested at the stage of two trifoliate leaves to fertilization; their level of significance and significant differential effects between lines

Dependent variable	Factor	Entry 1	Entry 2	Entry 3	Mean squares	F
%P	b_o	0.2789**	0.2632**	0.2594**	0.0002	< 1
	P	0.2375**	0.2042**	0.2486**	0.0021	< 1
	K	-0.0670*	-0.0472+	-0.0989*	0.0028	1.15
	Ca	-0.1063**	-0.1331**	-0.1352**	0.0011	< 1
	P^2	0.0204**	0.0296**	0.0270**	0.0019	< 1
	K^2	0.0152*	0.0105+	0.0228*	0.0033	1.34
	Ca^2	0.0238**	0.0307**	0.0319**	0.0016	< 1
	PK	-0.0115++	-0.0034	-0.0063	0.0020	< 1
	PCa	-0.0281**	-0.0283**	-0.0396**	0.0053	2.17+
	KCa	0.0018	0.0013	0.0030	0.0001	< 1
	PKCa	0.0002	-0.0014	-0.0015	0.0009	< 1
	R^2	0.9743	0.9779	0.9589		
	Experimental error				0.00245	
%K	b_o	1.9464**	1.8848**	2.0535**	0.0170	< 1
	P	0.1561	0.1688++	0.3036**	0.0258	< 1
	K	0.6406**	0.5249**	0.6473**	0.0196	< 1
	Ca	-0.2059+	-0.2844**	-0.4607**	0.0707	2.50++
	P^2	-0.0117	-0.0085	-0.0443*	0.0339	1.20
	K^2	-0.1278**	-0.0912**	-0.1223**	0.0335	1.18
	Ca^2	0.0366+	0.0502*	0.0821**	0.0471	1.66+
	PK	0.0624*	0.0352++	0.0696**	0.0389	1.37
	PCa	-0.0233	-0.0099	-0.0057	0.0104	< 1
	KCa	0.0200	0.0155	0.0322++	0.0100	< 1
	PKCa	-0.0032	-0.0065	-0.0090+	0.0089	< 1
	R^2	0.8570	0.8725	0.9320		
	Experimental error				0.02834	

Table 120. (Continued)

Dependent variable	Factor	Entry 1	Entry 2	Entry 3	Mean squares	F
%N	b_o	4.9839**	4.9081**	4.8349**	0.0130	< 1
	P	0.0310	0.1088	0.0556	0.0061	< 1
	K	-0.1948	0.0498	-0.2522++	0.1063	1.95+
	Ca	-0.2396+	-0.2773*	-0.2561++	0.0015	< 1
	P^2	0.0135	0.0066	0.0165	0.0022	< 1
	K^2	0.0324	-0.0148	0.0456+	0.0867	1.59+
	Ca^2	0.0641++	0.0702**	0.0562++	0.0042	< 1
	PK	0.0297	0.0071	0.0063	0.0208	< 1
	PCa	-0.0190	-0.0266+	-0.0069	0.0122	< 1
	KCa	-0.0006	-0.0030	0.0217	0.0246	< 1
	PKCa	-0.0017	0.0006	-0.0038	0.0051	< 1
	R^2	0.4059	0.4879	0.5151		
	Experimental error				0.05446	

The largest change in level of significance from combination of the data occurred for the effect of P on the percent N in the leaves. It changed from insignificance to the 0.01 level of significance (Table 121).

Duncan's multiple range test showed that only PCa responses affected the percent P in the leaves differentially at this early stage of development (Table 122). The differential responses of the percent K in the leaves at this stage were due to Ca, whereas at the seven-leafed stage they were caused by K and at the end of flowering by P. This shift in emphasis with stage of development is not easily explained biologically. A partial explanation may be that the percent K of the leaves was rather strongly affected by Ca at the youngest stage (Table 120). The changes

Table 121. Partial regression coefficients, b_i, of the combined equations for the chemical composition of the leaves at the two trifoliate-leafed stage for three elements in 1963; t-values and their significance

Dependent variable	Factor	b_i	t
%P	b_o	0.2589	16.43**
	P	0.2341	16.73**
	K	-0.0669	5.09**
	Ca	-0.1208	9.21**
	P^2	0.0257	8.35**
	K^2	0.0162	5.25**
	Ca^2	0.0288	9.34**
	PK	-0.0091	5.23**
	V_1xPCa	-0.0322	15.69**
	V_2xPCa	-0.0327	15.90**
	V_3xPCa	-0.0365	17.79**
	R^2	0.9656	
%K	b_o	1.9616	30.85**
	P	0.2095	4.24**
	K	0.6043	12.64**
	V_1xCa	-0.2523	4.43**
	V_2xCa	-0.4826	8.47**
	V_3xCa	-0.2161	3.79**
	P^2	-0.0215	2.06*
	K^2	-0.1138	10.86**
	V_1xCa^2	0.0413	3.06**
	V_2xCa^2	0.0870	6.45**
	V_3xCa^2	0.0406	3.01**
	PK	0.0557	6.23**
	PCa	-0.0130	1.48+
	KCa	0.0225	2.68**
	PKCa	-0.0062	2.06*
	R^2	0.8673	

Table 121. (Continued)

Dependent variable	Factor	b_i	t
%N	b_o	4.8345	72.89**
	P	0.1438	6.01**
	V_1xK	-0.1196	1.63+
	V_2xK	0.0534	0.73
	V_3xK	-0.2792	3.80**
	Ca	-0.2628	4.50**
	V_1xK^2	0.0292	1.51+
	V_2xK^2	-0.0122	0.63
	V_3xK^2	0.0592	3.07**
	Ca^2	0.0675	4.94**
	PCa	-0.0212	2.42*
	R^2	0.4858	

of obtaining a significant difference between corresponding partial regression coefficients are then also increased. This would indicate that the meaning of the results from a single test in a detailed analysis should not be over-emphasized and should rather be interpreted in conjunction with other results.

A number of contour maps were produced. All of them had P and K application as variables, holding applied Ca constant at the rate of 2000 pp2m. All were for the same two lines of soybeans at all three stages of development to facilitate comparison of the development of differential effects with time. Responses and differential responses of interest

Table 122. Comparison of corresponding partial regression coefficients in the combined equations for the chemical composition with respect to three elements in the leaves of three soybean lines at the stage of two trifoliate leaves in 1963, using Duncan's multiple range test

Independent variable	Nature of differential response	Line, regression coefficients and significance of differences[a]		
%P	PCa	3	2	1
		-0.0365	-0.0327	-0.0322
%K	Ca	2	1	3
		-0.4826	-0.2523	-0.2161
	Ca^2	3	1	2
		0.0406	0.0413	0.0870
%N	K	3	1	2
		-0.2792	-0.1196	0.0534
	K^2	2	1	3
		-0.0122	0.0292	0.0592

[a]Comparisons failing to reach the 0.05 level of significance are underlined with a solid line. In addition, those reaching the 0.05 level but not the 0.01 level of significance are indicated with a broken line.

were read from the graphs and are given in Table 123. The response of Entries 1 and 2 to 300 pp2m P at levels of 400 pp2m K and 2000 pp2m Ca were large under the influence of highly significant P effects. The highly significant differential effect of P between the two lines (Table 116) was of considerable magnitude at the selected rate of fertilization (Table 123). At the seven-leafed stage the effect of 300 pp2m P were also large. The differential effects were of negligible

Table 123. Magnitude of predicted responses and differential responses of the nutrient composition of the leaves to P, K and Ca application involving one or more significant effects in several soybean lines, grown in pots in 1963 and harvested at three stages of growth

Dependent variable	Stage of growth	Entry	Factor specification P	K	Ca	Percentage composition from	to	response	Differential response
%P	End of	1	0-300	400	2000	0.10	0.48	0.38	
	flowering	2	0-300	400	2000	0.10	0.29	0.19	0.19
	Seven-	1	0-300	400	2000	0.12	0.55	0.43	
	leafed	2	0-300	400	2000	0.15	0.55	0.40	0.03
	Two-	1	0-300	400	2000	0.10	0.50	0.40	
	leafed	2	0-300	400	2000	0.08	0.48	0.40	0.00
%K	End of	1	0-300	400	2000	2.05	1.95	0.10	
	flowering	3	0-300	400	2000	1.95	1.95	0.00	0.10
		1	300	0-400	2000	0.90	2.05	1.05	
		3	300	0-400	2000	1.10	2.00	0.90	
	Seven-	1	300	0-400	2000	1.60	2.50	0.90	
	leafed	3	300	0-400	2000	1.70	2.60	0.90	0.00
	Two-	1	300	0-400	2000	1.80	2.90	1.10	
	leafed	3	300	0-400	2000	1.80	3.00	1.20	
%Ca	End of	1	0-300	400	2000	1.35	1.60	0.25	
	flowering	2	0-300	400	2000	1.43	1.72	0.29	
		1	300	0-400	2000	2.00	1.60	-0.40	
		2	300	0-400	2000	2.20	1.72	-0.48	

Table 123. (Continued)

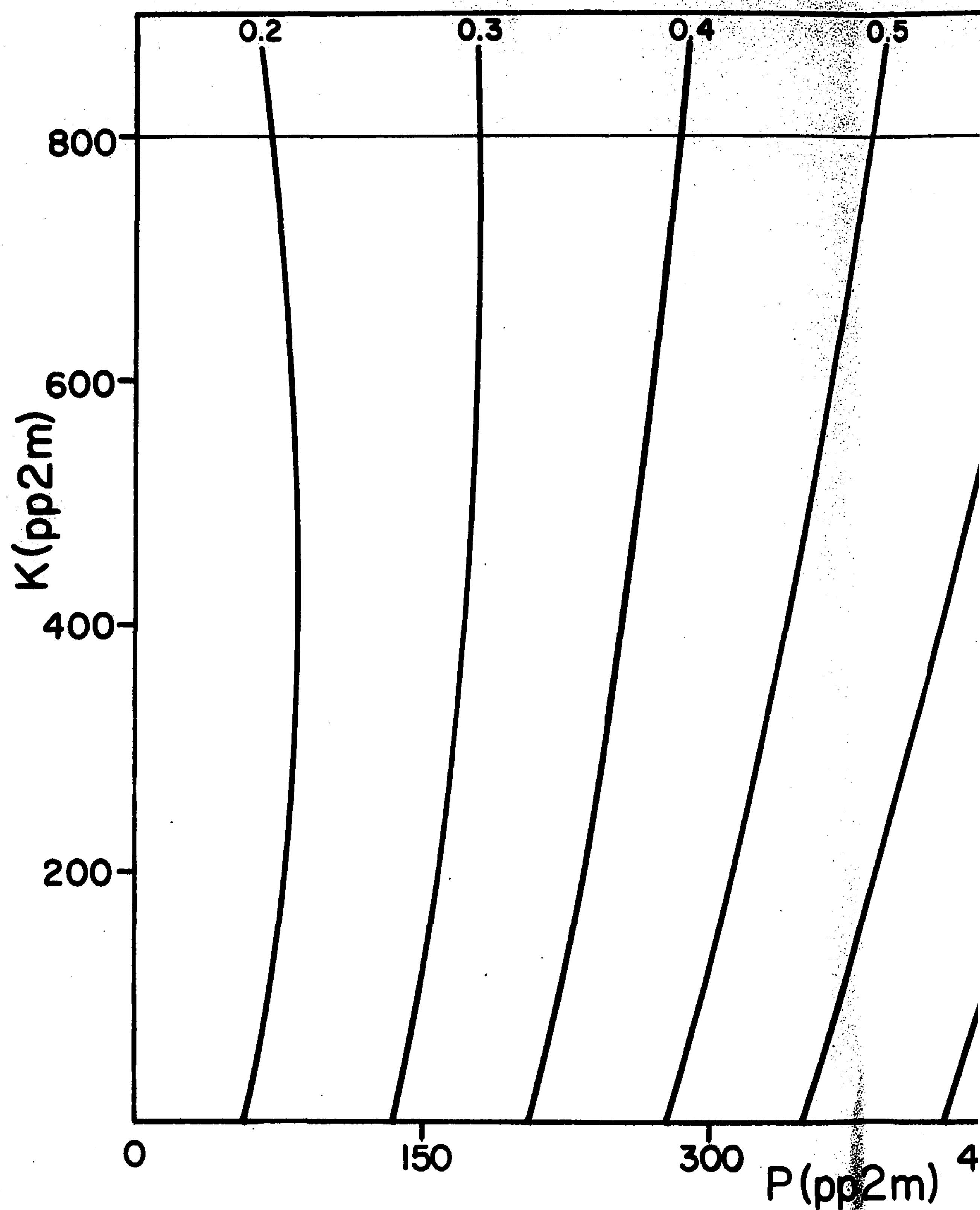
Dependent variable	Stage of growth	Entry	Factor specification P	K	Ca	Percentage composition from	to	response	Differential response
%Mg	End of flowering	1	0-300	400	2000	0.37	0.45	0.08	
		2	0-300	400	2000	0.38	0.45	0.07	
		1	300	0-400	2000	0.65	0.45	-0.20	
		2	300	0-400	2000	0.70	0.45	-0.25	0.05
%N	End of flowering	1	0-300	400	2000	3.30	4.75	1.45	
		2	0-300	400	2000	3.20	4.20	1.00	0.45
		1	300	0-400	2000	4.40	4.75	0.35	
		2	300	0-400	2000	3.88	4.20	0.32	
	Seven-leafed	1	0-300	400	2000	4.00	4.70	0.70	
		2	0-300	400	2000	3.80	4.45	0.65	
	Two-leafed	1	0-300	400	2000	2.50	2.65	0.15	
		2	0-300	400	2000	2.65	2.83	0.18	

magnitude, despite the fact that highly significant differential effects due to P^2, PK and PCa were recorded (Table 119). Some of these effects had opposite signs and their collective effect was of negligible size at the rate of fertilization presently considered. At the two-leafed stage the responses to P application were large. No differential effects were indicated in Table 122 and none were found. Although the detailed analysis of differential effects existing between every pair of varieties provides useful information, the predicted magnitude of their collective effect is the ultimate objective of practical importance. Real interest moreover is confined to the area of rational production. To extrapolate the results from the selected examples of fertilization under discussion to a wider region of fertilization it is necessary to inspect the contour maps and to interpret these in pairs for differential effects. Figures 41 through 44 illustrate this for the percent P in the leaves of Entry 1 and Entry 2. It may be seen from Figures 41 and 42 that the differences in percent P at the end of flowering increased with higher rates of P. Those at the seven-leafed stage were smaller but are not shown. Figures 43 and 44 show clearly that no predicted differential responses in percent P existed at any level of P and K fertilization in the youngest stage of development.

Responses in percent K due to P were small for both lines in the example given in Table 123. It appears from Figures 45 and 46 that stronger responses occurred only at high levels of P and K application. Differential responses were confined to the area of high P and low K application. The effects of K on the percent K in the leaves were large

Figure 41. Contours of percent P in the leaves at the end of flowering for Entry 1, grown in pots in 1963, as a function of P and K, holding Ca constant at 2000 pp2m

——————— Limits of investigated area


0.2
0.3
0.4
0.5
800
600
400
200
K(pp2m)
0
150
300
4
P(pp2m)

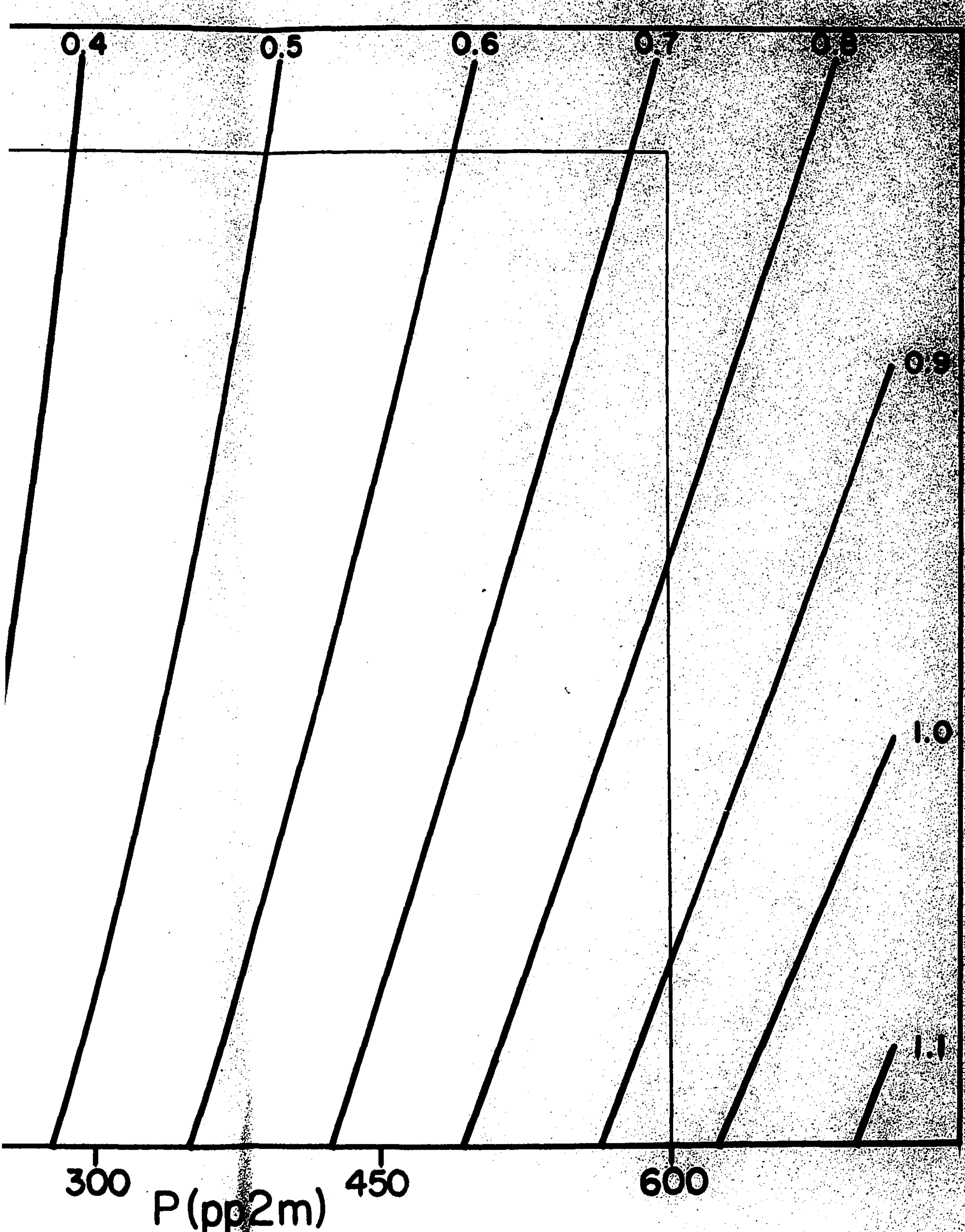
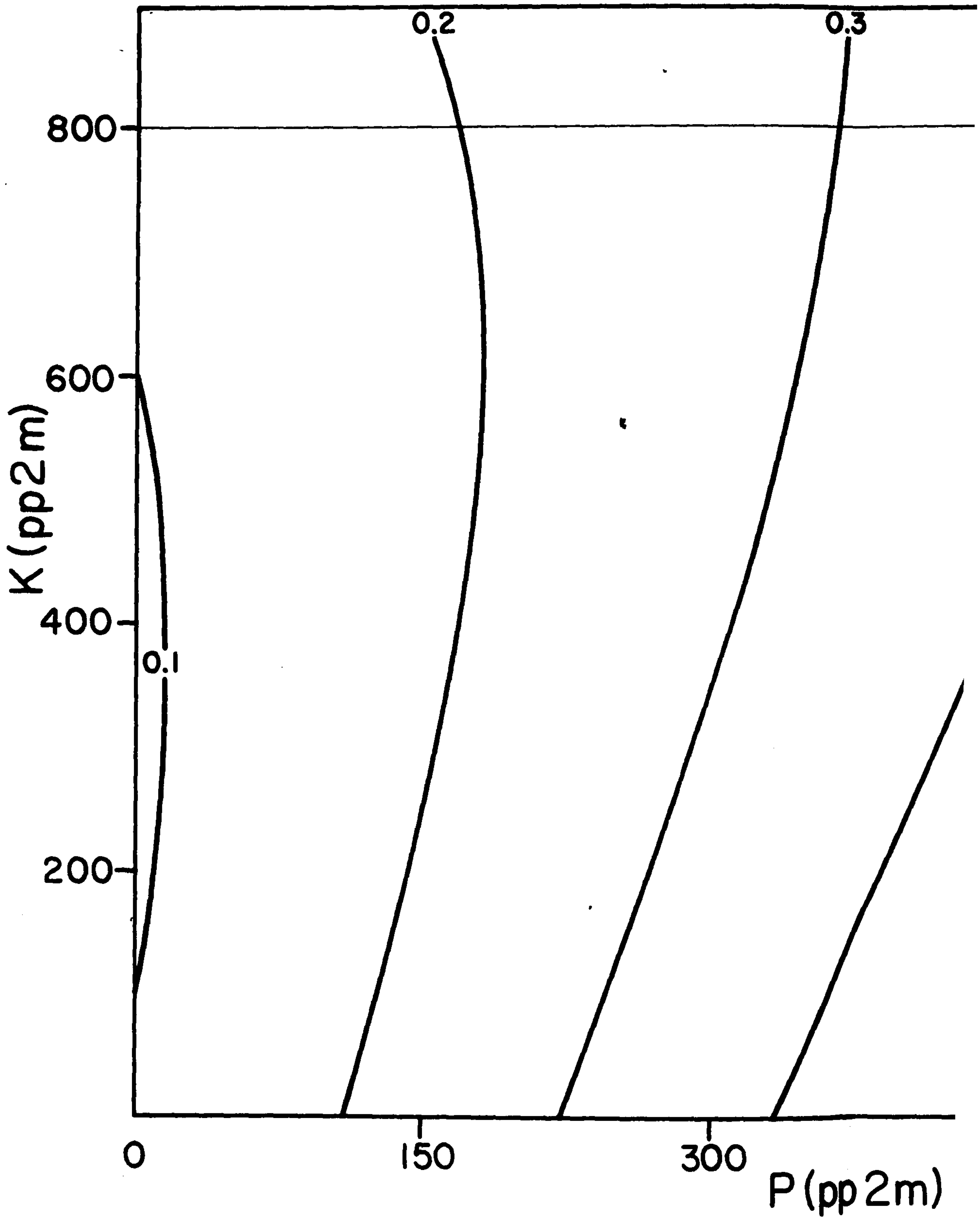

0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
300
450
600
P (pp2m)

Figure 42. Contours of percent P in the leaves at the end of flowering for Entry 2, grown in pots in 1963, as a function of P and K, holding Ca constant at 2000 pp2m

——————— Limits of investigated area



0.2
0.3
0.1
800
600
400
200
K (pp2m)
0
150
300
P (pp2m)

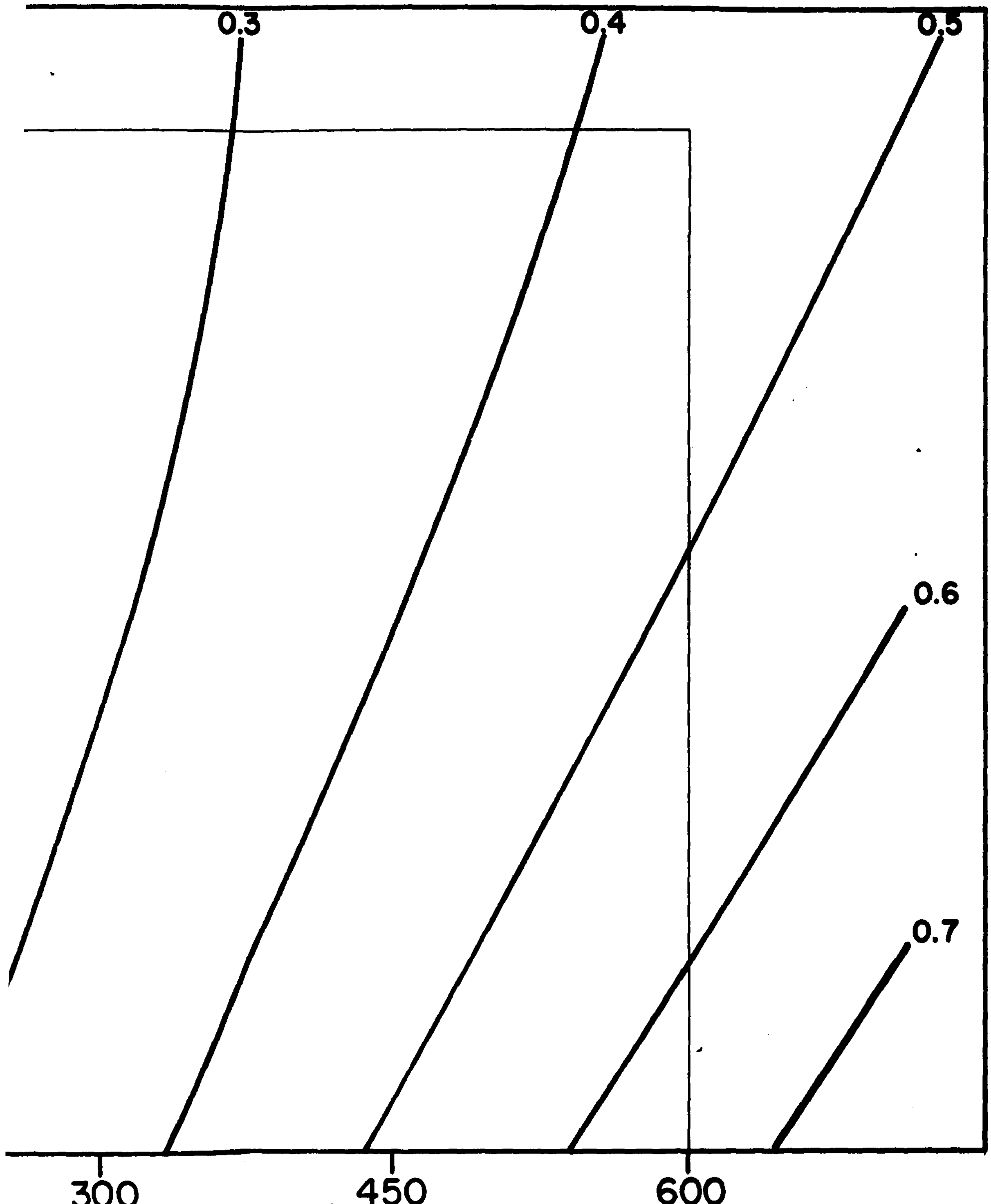
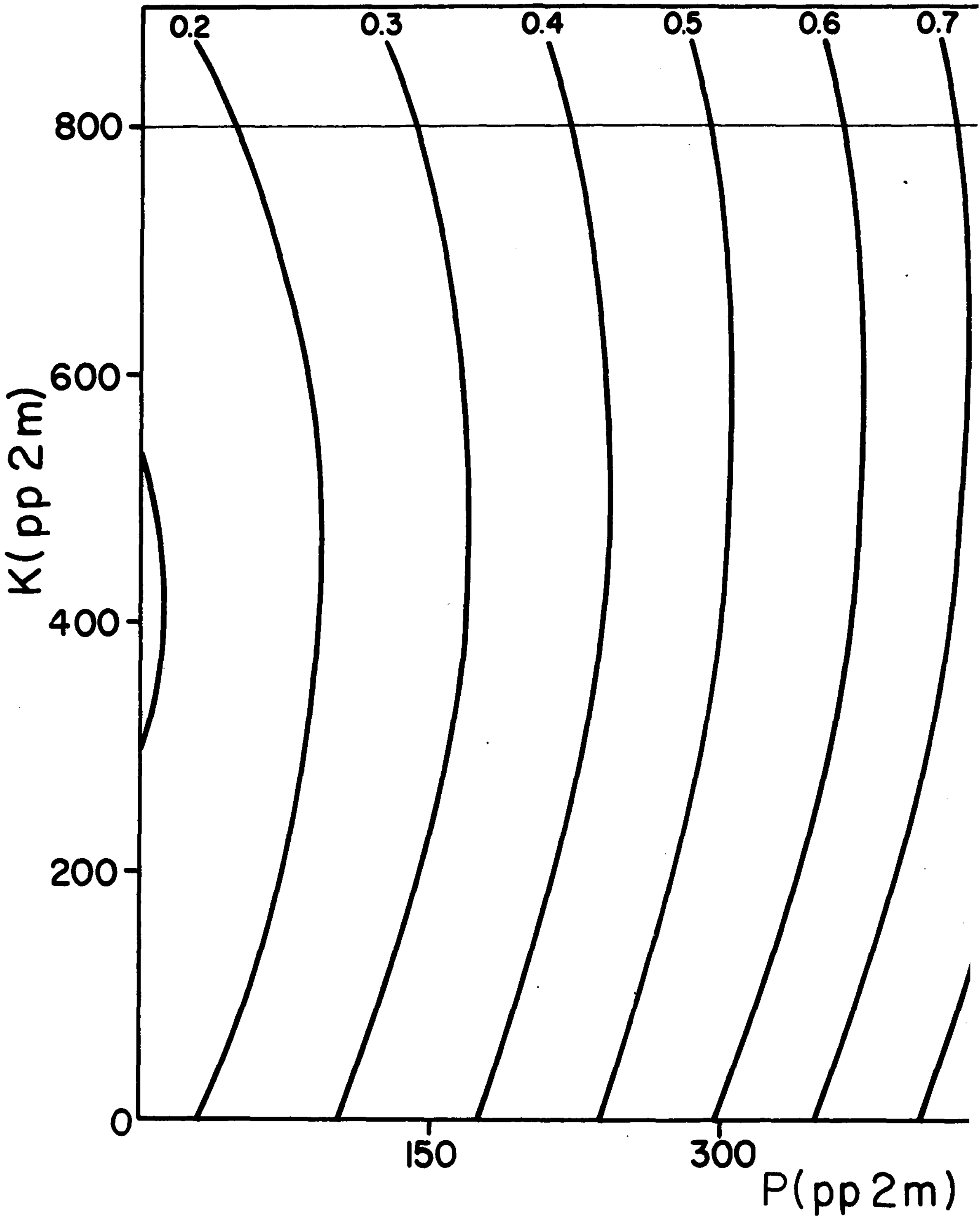

0.3
0.4
0.5
0.6
0.7
300
450
600
P (pp 2m)

Figure 43. Contours of percent P in the leaves at the stage of two trifoliate leaves, for Entry 1, grown in pots in 1963, as a function of P and K, holding Ca constant at 2000 pp2m

——————— Limits of investigated area


0.2
0.3
0.4
0.5
0.6
0.7
800
600
400
200
0
K(pp 2m)
150
300
P(pp 2m)

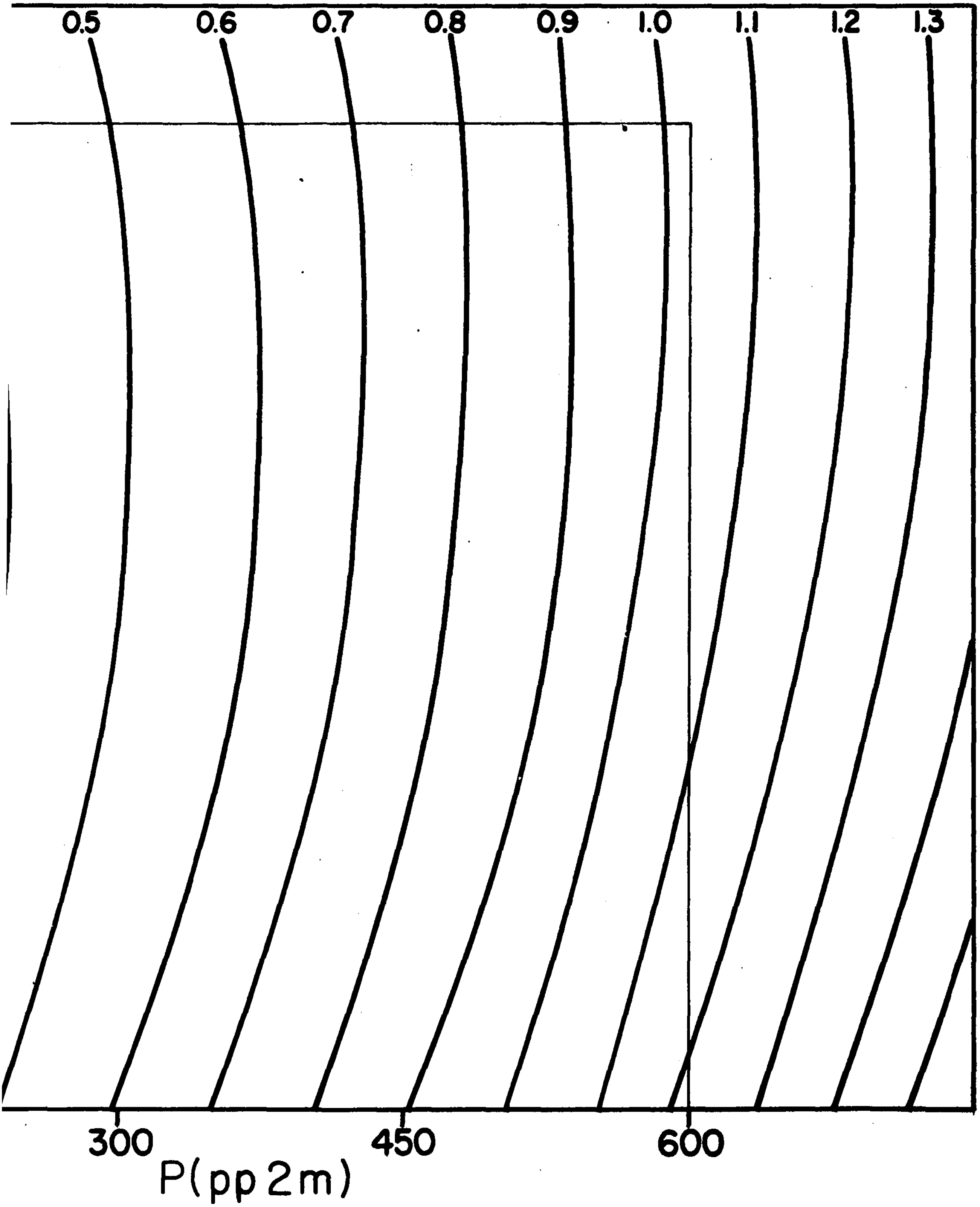
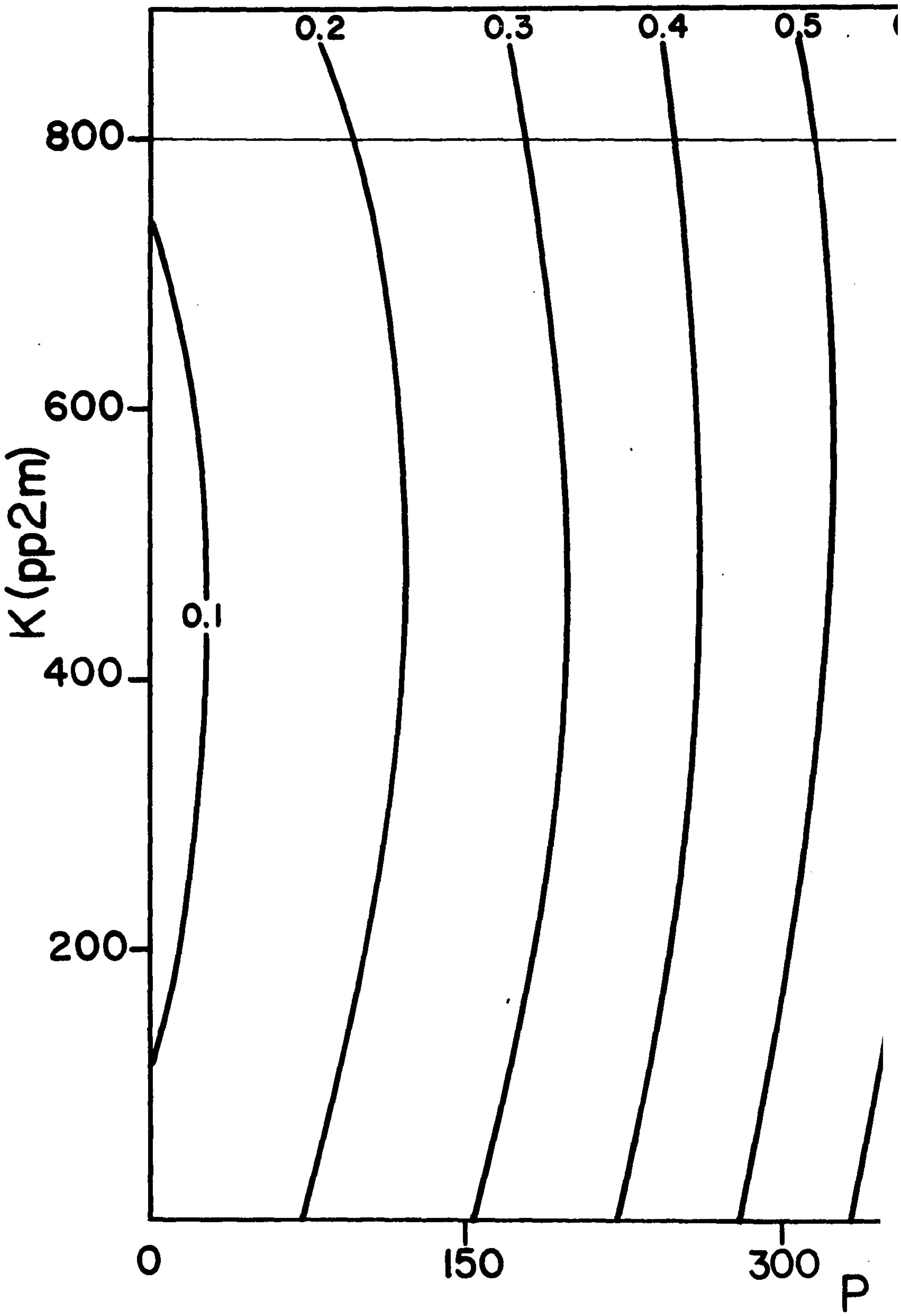
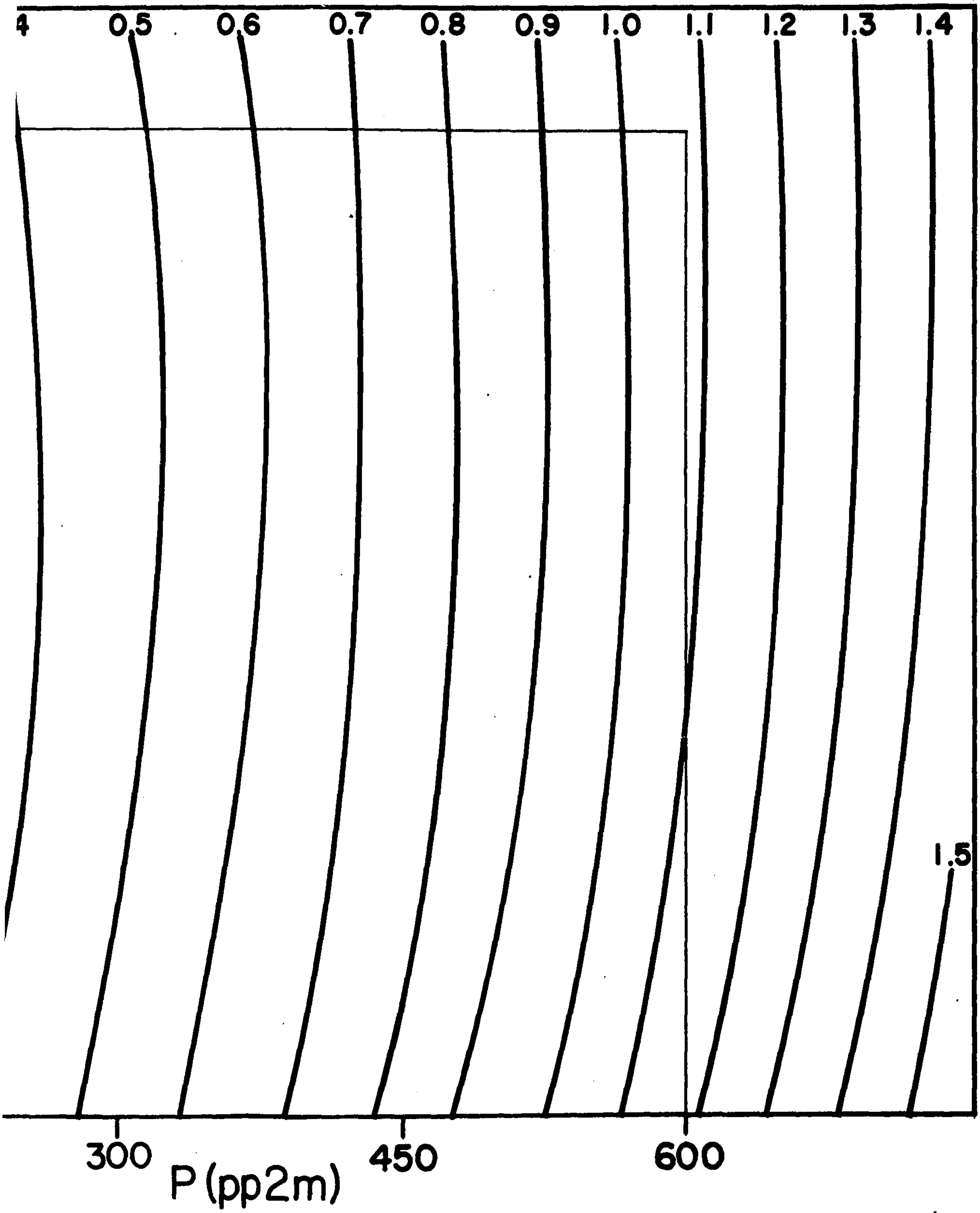

0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
300
450
600
P(pp 2m)

Figure 44. Contours of percent P in the leaves at the stage of two trifoliate leaves, for Entry 2, grown in pots in 1963, as a function of P and K, holding Ca constant at 2000 pp2m

——————— Limits of investigated area

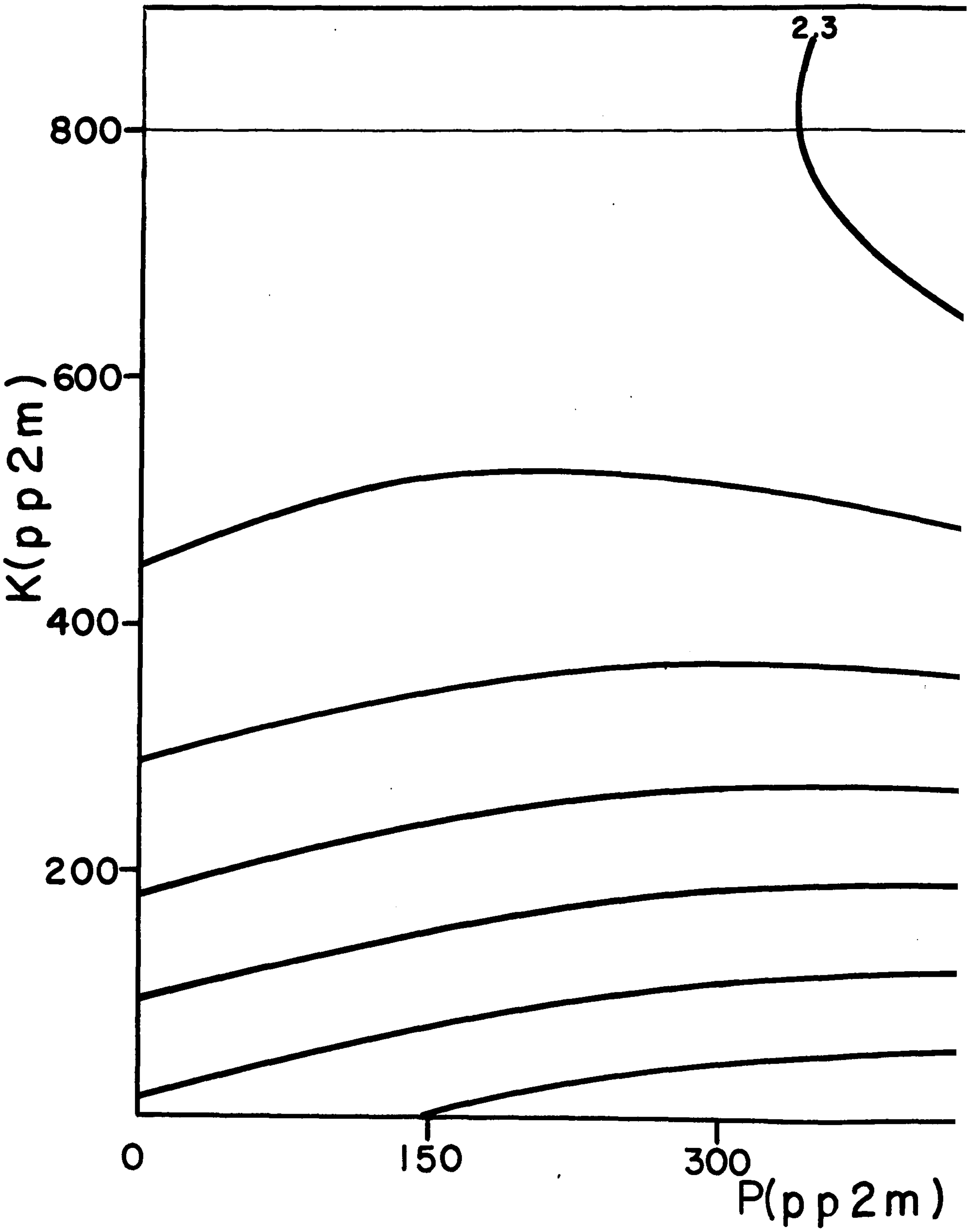

0.2
0.3
0.4
0.5
0.1
800
600
400
200
K (pp2m)
0
150
300
P



4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
300
450
600
P (pp2m)

Figure 45. Contours of percent K in the leaves at the end of flowering for Entry 1, grown in pots in 1963, as a function of P and K, holding Ca constant at 2000 pp2m

——————— Limits of investigated area


2,3
800
600
400
200
K(pp2m)
0
150
300
P(pp2m)

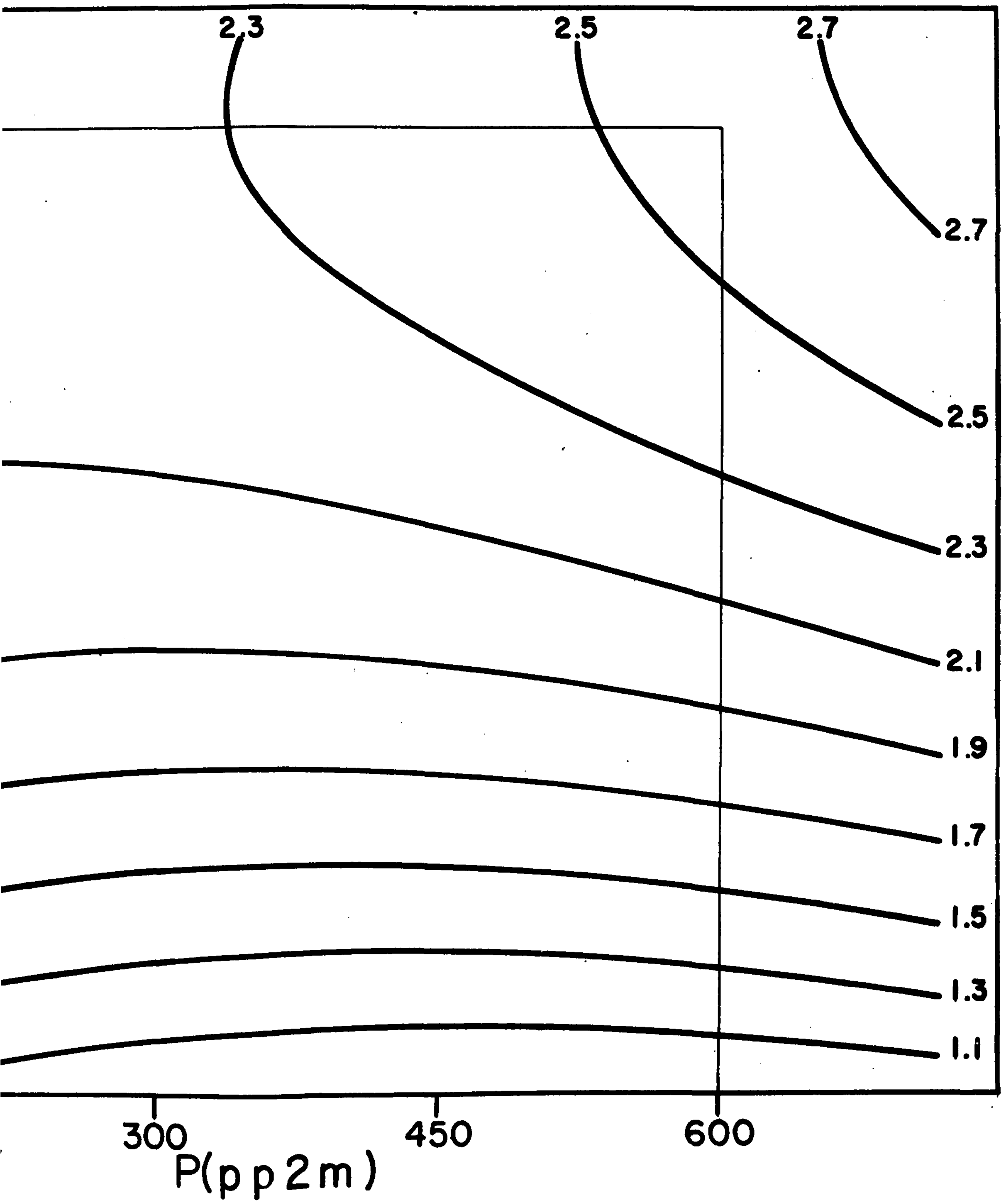
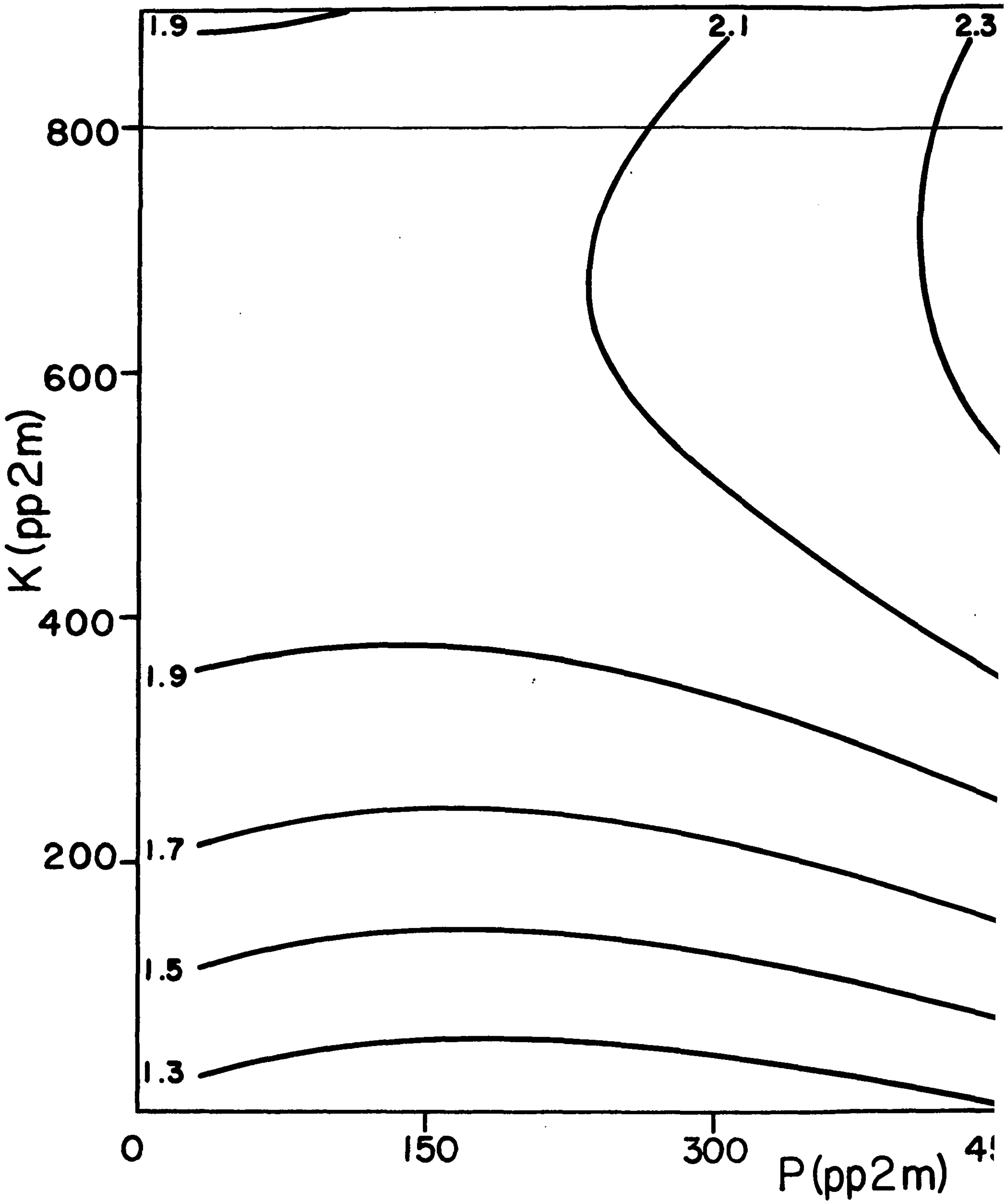
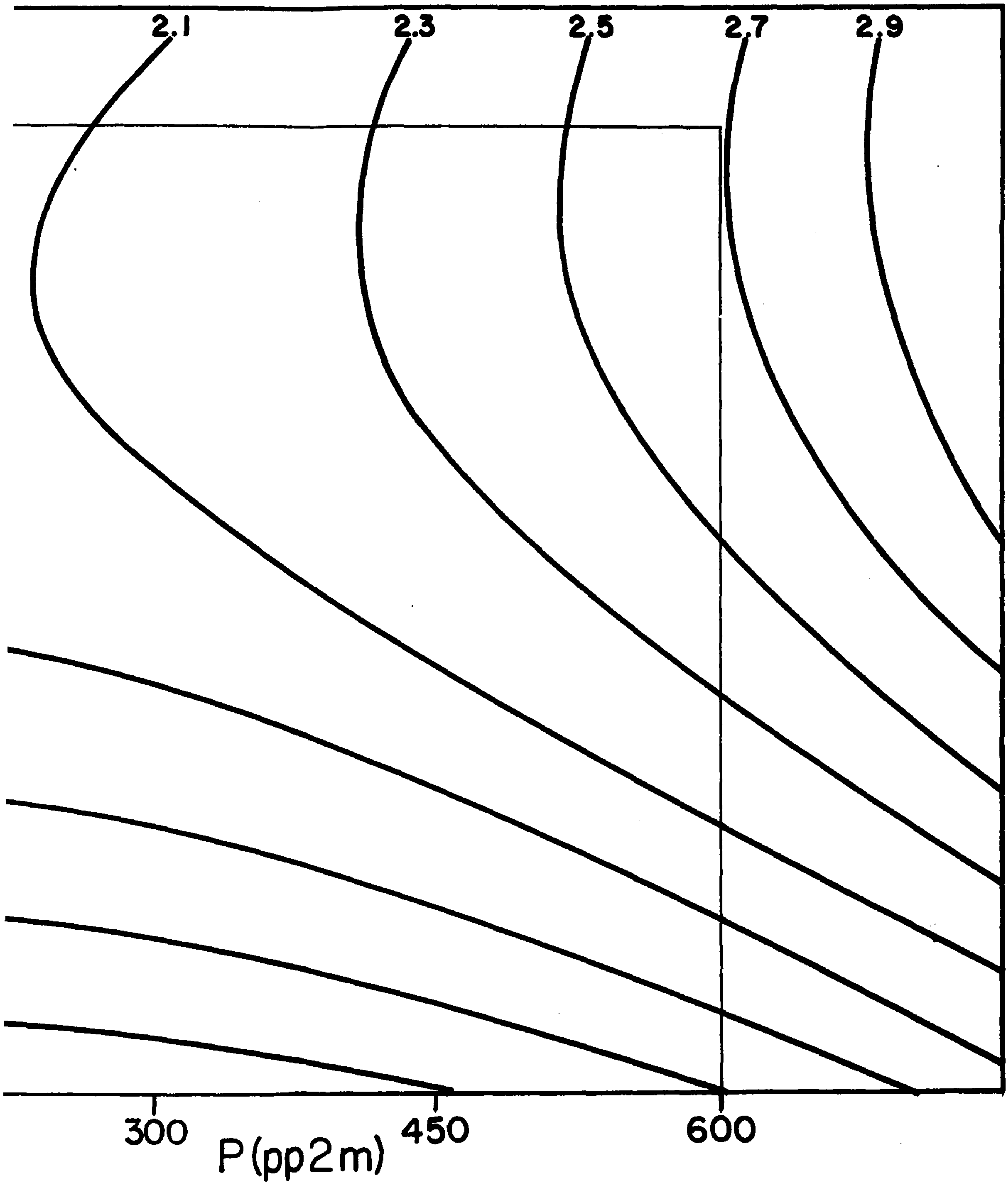

2.3
2.5
2.7
2.7
2.5
2.3
2.1
1.9
1.7
1.5
1.3
1.1
300
450
600
P(pp2m)

Figure 46. Contours of percent K in the leaves at the end of flowering for Entry 3, grown in pots in 1963, as a function of P and K, holding Ca constant at 2000 pp2m

——————— Limits of investigated area


1.9
2.1
2.3
800
600
K (pp2m)
400
1.9
1.7
200
1.5
1.3
0
150
300
P (pp2m)



2.1
2.3
2.5
2.7
2.9
300
450
600
P (pp2m)

at all stages and for both lines. The resultant of the highly significant differential effects of K, PK and PKCa at the seven-leafed stage was zero under the conditions listed in Table 123. No differential effects due to the factors P and K existed in the area of fertilization at the two-leafed stage.

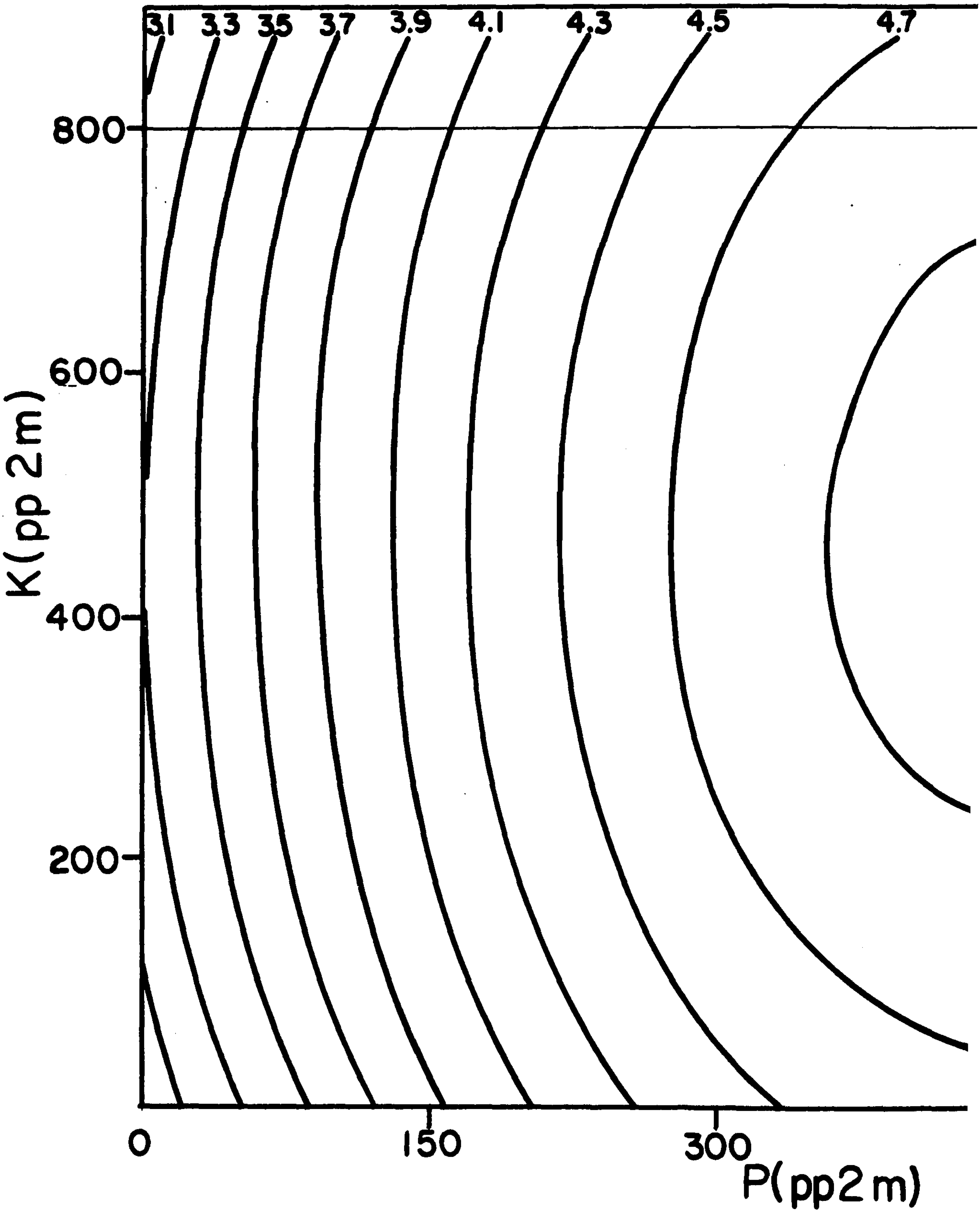
Large responses and differential responses of the percent N in the leaves to P application occurred at the end of flowering (Figures 47 and 48).

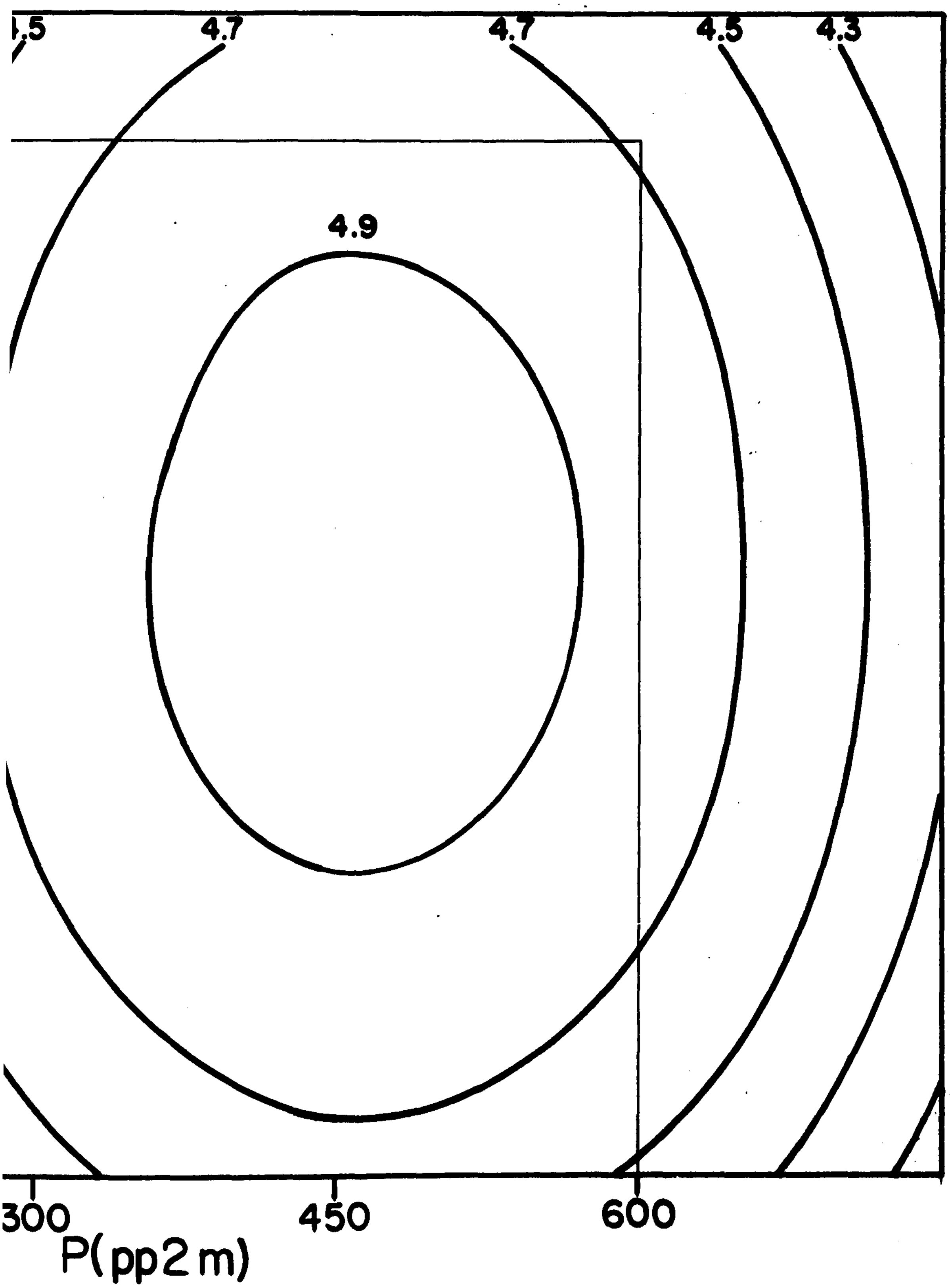
The range in nutrient content of the leaves from no fertilization to that required for maximum content is given in Table 124. The range in the predicted percent P was very wide and decreased after the seven-leafed stage. The range in percent K was also very wide and decreased after the two-leafed stage. The range in percent N widened after the two-leafed stage as may be expected since the volume of activity of the nodule bacteria would gradually increase.

Critical nutrient percentages were determined for the yield of soybeans of each line using the fertilizer combinations from Table 98 and the multiple regression equations for leaf composition at the end of flowering listed in Table 114. The results are given in Table 125. The critical percentage of P in the leaves of Entry 1 appears higher than for the other two lines. Presumably this represents a real difference since highly significant differential responses in percent P of the leaves at the end of flowering were found and Entry 1 had a higher P content in the leaves than Entry 2 over the entire investigated region (Figures 41 and 42). The difference in percent N between Entry 1 and Entry 2 is

Figure 47. Contours of percent N in the leaves at the end of flowering for Entry 1, grown in pots in 1963, as a function of P and K, holding Ca constant at 2000 pp2m

——————— Limits of investigated area

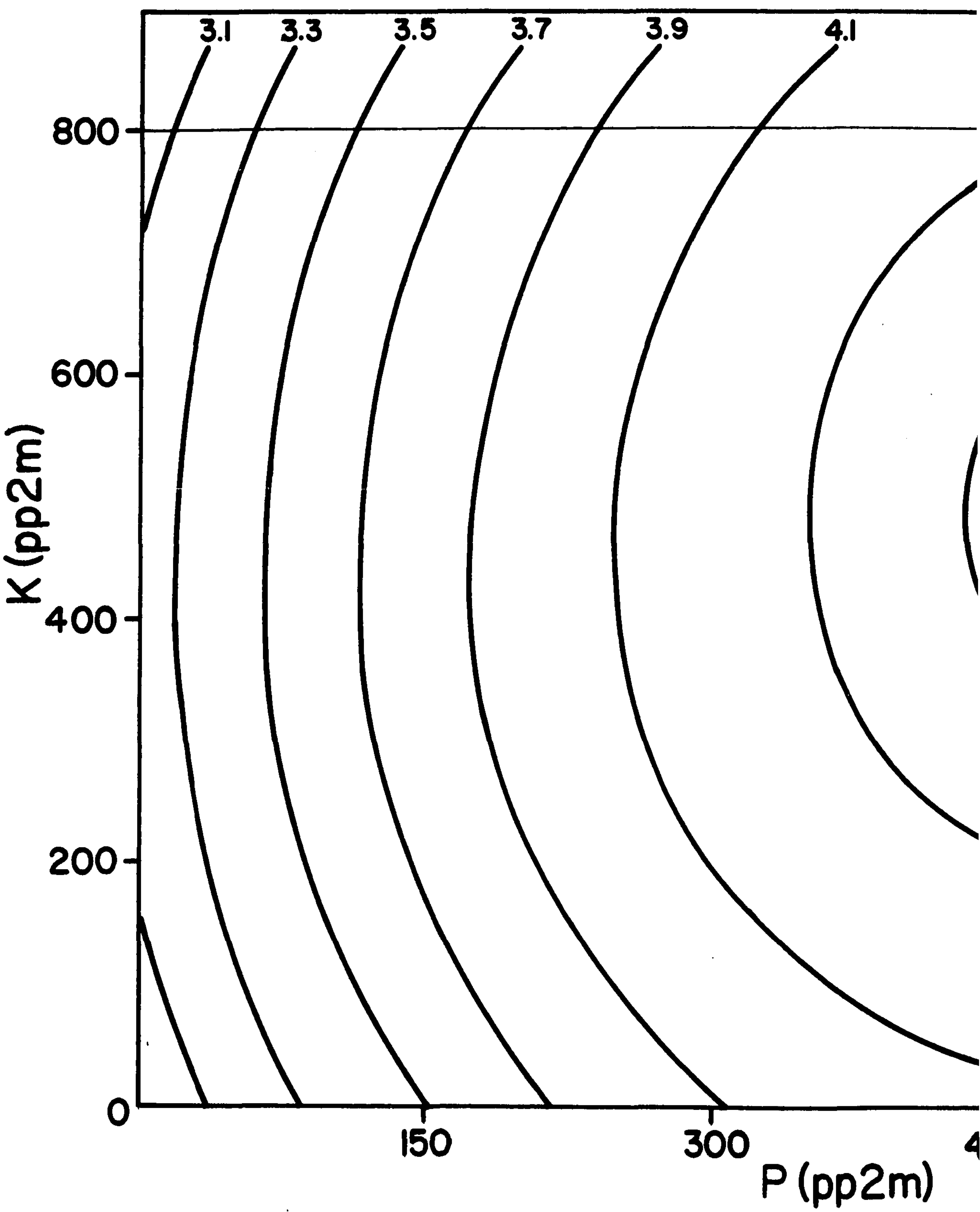

3.1
3.3
3.5
3.7
3.9
4.1
4.3
4.5
4.7
800
600
400
200
K(pp 2m)
0
150
300
P(pp2m)

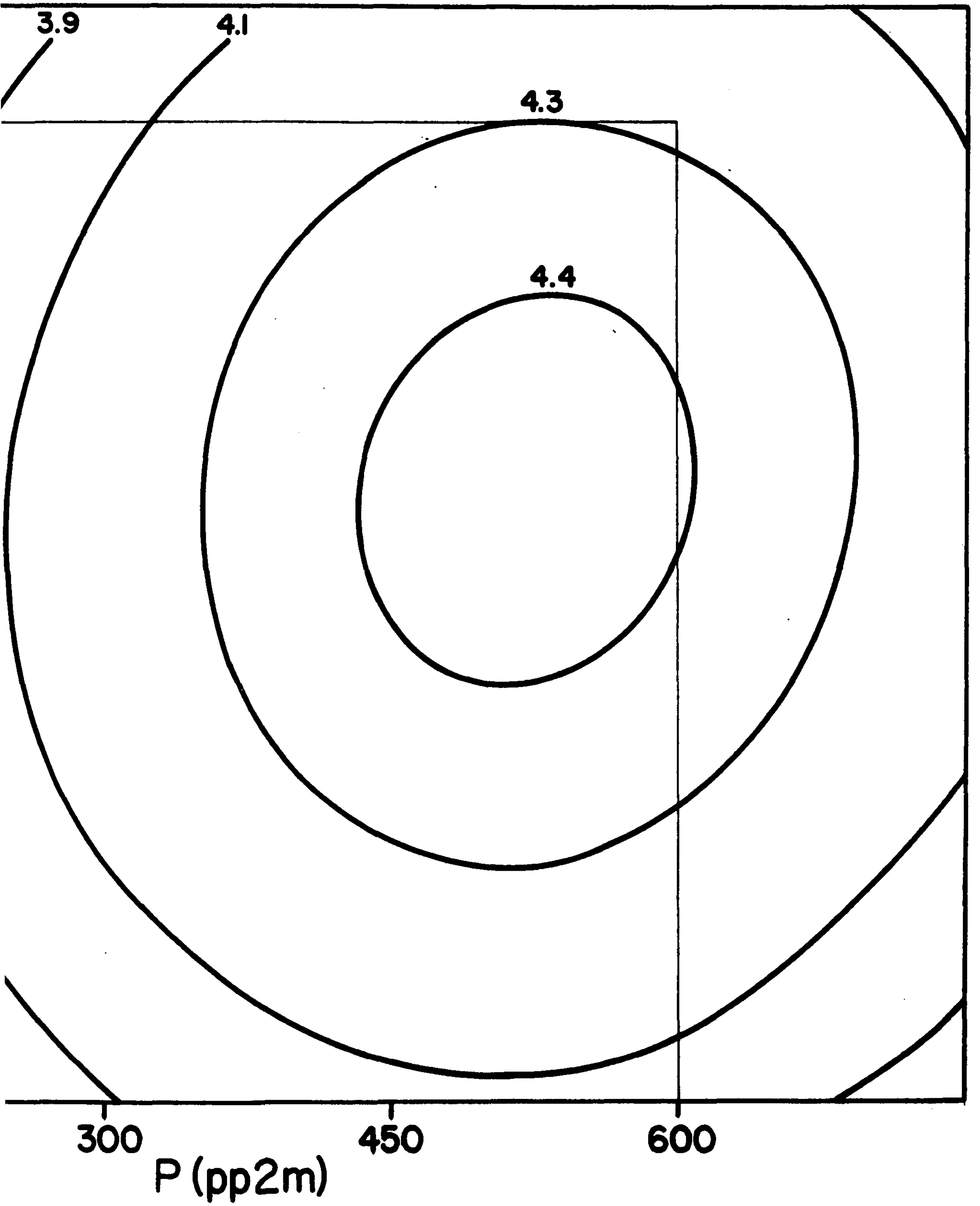


.5
4.7
4.7
4.5
4.3
4.9
300
450
600
P(pp2m)

Figure 48. Contours of percent N in the leaves at the end of flowering for Entry 2, grown in pots in 1963, as a function of P and K, holding Ca constant at 2000 pp2m

——————— Limits of investigated area


3.1
3.3
3.5
3.7
3.9
4.1
800
600
400
200
0
K (pp2m)
150
300
P (pp2m)



3.9
4.1
4.3
4.4
300
450
600
P (pp2m)

Table 124. P and K fertilizer combinations required for the maximum percentage content of nutrients in the leaves within the investigated region of fertilization and predicted range of nutrient content of the leaves of several soybean lines, grown in pots in 1963 and harvested at three stages of growth, with Ca held constant at a rate of 2000 pp2m

Dependent variable	Stage of growth	Entry	Fertilizer combination pp2m		Range	
			P	K	Check	Max
%P	End of flowering	1	600	0	0.15	0.95
		2	600	0	0.10	0.65
	Seven-leafed	1	600	0	0.20	1.30
		2	600	0	0.10	1.50
	Two-leafed	1	600	0	0.15	1.20
		2	600	0	0.15	1.20
%K	End of flowering	1	600	800	1.25	2.60
		3	600	800	1.25	2.70
	Seven-leafed	1	600	800	1.70	3.08
		3	600	800	1.70	2.90
	Two-leafed	1	600	800	1.60	3.70
		3	600	800	1.50	3.63
%Ca	End of flowering	1	490	0	1.60	2.10
		2	600	0	1.80	2.30
%Mg	End of flowering	1	600	0	0.50	0.68
		2	600	0	0.55	0.73
%N	End of flowering	1	465	480	2.90	5.00
		2	520	500	2.90	4.40
	Two-leafed	1	600	800	2.75	3.10
		2	600	560	2.65	3.04

Table 125. Critical percentages of nutrients in the leaves of several lines grown in pots in 1963 for the yield of soybeans at maturity and for fresh-weight production at the two-leafed stage, with associated leaf contents of Mg and N

Product	Stage at time of leaf analysis	Entry	%P	%K	%Ca	%Mg	%N
Yield of soybeans	End of flowering	1	0.54	2.33	1.53	0.39	4.96
		2	0.38	1.84	1.59	0.36	4.39
		3	0.42	2.27	1.40	0.32	4.83
Fresh weight tops at two-leafed stage	Two-leafed	1	1.14	3.64			5.20
		2	0.95	3.24			5.33
Fresh weight tops at two-leafed stage	End of flowering	1	0.88	2.36			5.32
		2	0.46	1.80			4.62

similarly substantiated by highly significant differences in Figures 47 and 48.

The N contents associated with maximum yield may not strictly be named critical contents because the supply was not a controlled variable in this experiment. It was, however, strongly influenced by P application via stimulation of nodulation. It seems justified to consider the percent N in conjunction with the percent P as critical contents in this leguminous plant species. It may be seen from Figures 47 and 48 that the percent N in the leaves at the maximum yield of soybeans was also the maximum percent N in the investigated region for both lines. The percent Mg in the leaves at maximum soybean production had no meaning as a critical content since the Mg supply from the soil may have been limiting.

The critical values for the production of fresh-weight of tops at the stage of two trifoliate leaves and evaluated on the basis of leaf composition at that same stage were calculated for comparison with the data obtained in the previous experiment. The values for the critical percentages of P and K in Table 125 were very high at this early stage. The values for the percent P bordered on the region of expected P toxicity symptoms. The values for the previous experiment (Table 87a) referred to the stage of 4.5 trifoliate leaves and appear in good agreement with the general downward trend in percent P and percent K with progressing stage of development existing in the leaves of soybean plants.

The critical percentages calculated for fresh-weight production of tops at the two-leafed stage were also expressed as leaf contents which would have prevailed if the plants had been grown until the end of flowering. The P contents were higher than the critical percentages for the yield of soybeans. This offers the suggestion that those plants receiving sufficient P to produce the fastest growth at early stages of development do not carry on to produce the maximum yield of soybeans.

5. Conclusions

Interveinal discoloration of the leaves appeared shortly after the two-leafed stage if high rates of P application were not accompanied by high rates of K and Ca application. There were visible differences in the degree of symptom development between the three soybean lines studied in the experiment. Entry 1 was the most tolerant and Entry 3 the most sensitive line. The symptoms were related to high P contents in the leaves at the stage of two trifoliate leaves and therefore are referred to as P toxicity symptoms.

Interpolation of observed values led to estimates of the minimum P content whereby the symptoms would appear. An average value for this content in the leaves of three soybean lines is 0.90 percent P at the stage of two trifoliate leaves. The K content of the leaves had no bearing on the symptoms. Neither had any of the other elements which were determined, except N. The P and N contents were correlated. New growth produced in later stages of development had a healthy appearance in many cases and the percent P in the leaves showed a corresponding reduction due to leaf drop and dilution effects in the plant.

Significant yield responses to P and K application and differential responses to P and PCa were found. Seed size was influenced by the same factors and differential responses were even more plentiful for this property. Examples of yield responses to P were of the order of 100% and differential responses reached 25% of the yield of pots receiving K and Ca, without P. Responses to K were of smaller although considerable magnitude. Maximum yield of soybeans involved very heavy fertilization with P and K. Applications of approximately 500 pp2m P, 660 pp2m K and 4000 pp2m Ca were optimal under the conditions of the experiment. Under these conditions all lines responded three-fold to fertilization.

The fresh-weight of the tops responded strongly to P application and in some cases to K and the PK or PCa interaction. Highly significant differential responses to P and its interactions with K and Ca existed at the end of flowering and to a lesser extent also at the seven-leafed stage. At the two-leafed stage there were varietal differences in the weight of green matter produced, but no differential responses to fertilizers of any consequence. It was found that the differences between the soybean lines were not necessarily in favor of the same line at all stages of development. Some may be expected to overtake others in rate of growth with time. The magnitude of the responses and differential responses in green weight was large and increased with the stage of development. They were largest at the end of flowering both on an absolute and a relative scale. Maximum green weight required high rates of all nutrients similar to those for maximum yield of grain. Entry 2 produced the highest amount of green weight in the early stages of growth, but outyielded the other lines by the end of flowering over the entire range of fertilization.

The nodulation was strongly stimulated by P application. The P, P^2 and PCa effects were most important for the number and weight of the nodules. Highly significant varietal differences existed at the seven-leafed stage and at the end of flowering. Entry 1 had the largest number at both stages but the smallest weight of nodules at the end of flowering. The weight of nodules of Entry 2 increased from the smallest at the seven-leafed stage to the largest by the end of flowering under unfertilized conditions. The most significant differential responses of nodule-weight found were due to P application and existed at both stages of development.

Responses in weight of nodules to P application approached 100% and differential responses were substantial also. The maximum number and weight of nodules at the end of flowering required 450 and 500 pp2m P. These conditions caused a three-fold rise in the weight of nodules. These facts correspond closely to the conclusions reached for the yield of grain. There is a striking agreement between these fertilizer combinations and those found for maximum green matter production at the 4.5-leafed stage in the pot experiment of 1962 which was conducted with two different soybean lines. The fertilization at the maximum then was 525 pp2m P, 725 pp2m K and 3500 pp2m Ca. These rates are almost identical with those quoted above for maximum yield in the 1963 experiment. It followed further from computation of predicted values that the number of nodules on the roots of the plant at least doubled between the seven-leafed stage and the end of flowering. Their weight was more than tripled during this period.

The composition of the leaves was strongly affected by fertilization. The P content was mainly influenced by the factors P, Ca and the interactions of P with K and Ca. This held generally at all three stages of development. The percent K was primarily affected by K, Ca and the KCa interaction and in some cases also by P and the PK interaction. The percentages Ca and Mg at the end of flowering were affected to high levels of significance by nearly all factors. The effect of Ca was perhaps of least significance. The main factor influencing the percent N was P. Other factors of significance were K, Ca and the PCa interaction. Differential effects were most pronounced at the end of flowering. The percent P particularly was subject to several and highly significant differential effects. Their combined effect was to raise the P content of Entry 1 to substantially higher levels than that of Entry 2 over the full region of P and K fertilization. Highly significant differential responses of the percent K existed but their combined effect as expressed in contour maps was not of practical interest. Those in percent N were primarily due to P and resulted in a considerably higher percent N in the leaves of Entry 1 than of Entry 2. This difference increased in size towards the location of the maximum. It was found that no differential responses of practical dimension existed in percent P, percent K, or percent N at young stages of development. They developed and reached a considerable size by the end of flowering for the percentages P and N.

It appears therefore that Entry 1 was more tolerant to high rates of P application in a young stage of development than Entry 2. At later stages it would possess a higher percent P and percent N in the leaves under any combination of fertilization and have a larger seed size. Entry 2 on the other hand out-yielded Entry 1 at any fertility level.

The predicted range in nutrient content of the leaves over the region of fertilization was wide for the percentages P, K and N. The range of percent N widened with further development of the plant, that of the percentages P and K narrowed to some extent at later stages.

Critical percentages for the yield of soybeans were computed and the critical percentages P and N for Entry 1 were found higher than for Entry 2. Although no standard errors could be calculated it was concluded that these differences reflected points from production surfaces which differed substantially for the two lines as a result of highly significant differential effects due to P.

The experiment demonstrated the dominant importance of nodulation characteristics for the yielding ability of soybean lines. Maximum yield of soybeans and maximum yield of green matter occurred at that combination of fertilizers where nodulation was optimal and the percent N in the leaves at the end of flowering was at a maximum.

V. COMPARISON OF THE RESULTS OBTAINED WITH POT AND FIELD EXPERIMENTS AND GENERAL CONCLUSIONS

The leaf symptoms which developed in the pot experiments were caused by P toxicity. Interveinal discoloration occurred at a leaf content of 0.90% P on the average and could not be prevented by doubling the K content of the leaves. By the end of flowering the percent P had fallen to lower levels by dilution and leaf drop. This situation prevailed when the root systems were restricted to the volume of soil in the pot. When not restricted at any time the trend in P content of the leaves is different, particularly when different soil is used and other environmental conditions prevail. The P-contents in the leaves and their trend with time as existing under field conditions were determined for the same soybean lines as used in the 1963 pot experiment. An experiment was conducted on a Webster clay-loam fertilized with the highest rates of P and K employed in the pot trial and three replications. Table 126 lists the mean values for the percent P in the leaves for each treatment and at three stages of growth. The percent P in the leaves was much lower than when the plants were grown in pots and the change in P content during development was strongly reduced also. The variety Hk was also grown in this experiment and conformed to the others. It may be expected that the four commercial varieties grown in the Howard County experiment showed a similar trend. The observed value of 0.44% P in the leaves at the end of flowering is therefore unlikely to have been much higher in younger stages when the symptoms appeared. It presumably fell far short of the 0.90% P

Table 126. Mean values of percent P in the leaves of three soybean lines grown in 1963 at the Agronomy Farm, South of Ames and harvested at three stages of growth; and fertilizer treatments

Stage of development	Fertilization (lbs./acre)			
	Check	600P	800K	600P 800K
Two-leafed	0.37	0.45	0.35	0.39
Seven-leafed	0.38	0.44	0.39	0.42
End of flowering	0.34	0.39	0.33	0.37

in the leaves at the two-leafed stage which was established as an average threshold value for P toxicity symptoms under the conditions of the pot trial. Also, the symptoms persisted in new growth produced up to the end of flowering. These facts suggest that the interveinal discoloration observed at the Howard County Experimental Farm were K-deficiency symptoms. Comparison of the leaf symptoms in Plates 5 and 13 shows distinct differences in pattern of discoloration. Those at the Howard County Farm are rather more restricted to the tip and periphery of the leaves which is in agreement with K-deficiency symptoms.

Highly significant responses in yield of soybeans to K application were found in the field experiments. No significant responses to P could be shown despite the fact the fertility level of the soils involved was low for P and K. Positive P responses could be recognized in production surfaces at high levels of K application, but they were too weak to be of statistical significance. In the pot experiment, on the other hand, P dominated the yield responses and were of the order of 100%

when 300 pp2m P were applied. K responses were less frequent and smaller because the soil used was moderately well provided with K. The maximum predicted response obtainable in the Howard County experiment was 12 to 14 bushels per acre, depending on the variety used. Most of this was due to K effects which therefore were of considerable size. In the Carrington-Clyde experiment the maximum K-responses were only one-fourth the size of those in the Howard County experiment. Differential responses due to K existed in the Carrington-Clyde experiment but were of negligible magnitude. Those in the Howard County experiment were due to P and also of negligible size. In the pot experiment differential responses to P were highly significant and of considerable size. The results from field and pot trials agreed with respect to rates of fertilization for maximum yield. Both indicated that maximum yield occurs at very high rates of fertilizer application. It was found that for three out of four varieties grown in the field the top rate of 400 pp2m P was insufficient to reach maximum yield and at that rate of P application between 500 and 580 pp2m K were required. The fourth variety was Chippewa. Its optimum for P was at 240 pp2m which may be explained in the light of the finding by Howell and Bernard (1962) that Chippewa is very sensitive to P toxicity. The pot trial indicated that close to 450 pp2m P and 650 pp2m K were required for maximum yield. At their maximum the lines grown in pots responded by a 3.5 to 3.6-fold yield increase, while the field-grown varieties responded by a factor 1.4.

Changes in leaf composition as a result of fertilization were highly significant both under field and pot conditions. In the field the percent

P responded to P and/or K application and in one trial differential responses to P application occurred. In the pot trial the percent P was largely affected by P and Ca application and there were highly significant differential responses to P. The percent K in the leaves was sensitive to K application in the field and to K and Ca in the pot trial. Differential effects existed in both cases and were more consistent and of larger size in the field. The percentages Ca and Mg were affected by many factors in the pot experiment. Ca was perhaps of least significance. P and K affected the percent Ca in the field and K had a strong influence on the percent Mg. K application depressed the percentages Ca and Mg in the leaves of plants grown in pots and in the field. The most striking difference occurred with respect to the percent N. The percent N was hardly influenced by fertilization in the field whereas it responded strongly to P in the pots and to some extent also to K. Differential effects between the soybean lines grown were significant and large, but non-existent in the field. The magnitude of the effects of fertilization on leaf composition for field and pot trials was summarized in Tables 50 and 123. Examples of predicted responses involving factors of statistical significance were determined by interpretation of contour maps at rates of P and K application which were equal in all cases and covered an area of practical interest. The percent K and especially the percentages P and N in the leaves were more strongly influenced in the pot experiments. It appeared, however, that the N level of the leaves in the field was close to 5% even without P application, while that in the pots was raised from 3 to 5%.

Multiple regression equations relating the yield of soybeans to the composition of the leaves for the nutrients P, K, Ca, Mg and N were developed for field experiments. They did not show significance for those elements which may be expected to be of real importance and the distribution of significant terms emphasized different factors for each variety. While the meaning of the results of the analysis was doubted it remained possible that the equations derived reflected real relationships. Similar relationships studied between dry-matter production of soybean plants at a young stage of development and leaf content of the elements P, K, Ca, Mg and N in pot trials were also unsatisfactory. Available data allowed expression of leaf composition in several forms and it appeared that the size and significance level of the partial regression coefficients varied unduly with the form of expression of the independent variables. It was suggested that the difficulties were caused by interdependence of the data for the five nutrients. The interference will be more serious the more nutrients are involved as independent variables and probably be worse for soybeans than for corn.

The critical percentages were listed in Table 49 for field conditions and in Table 125 for conditions prevailing in pot trials. They show fairly comparable levels for the percentages P, K and Ca under the different conditions. One soybean line, Entry 1 had a considerably higher critical percent P in the leaves at the end of flowering than the others. Entry 1 was also the most tolerant to high P application in young stages of development and this may be a desirable property for plant breeding purposes. Grown in the field with 47 other lines at rather high soil fertility levels Entry 1 reached the maximum P-content in the leaves (0.40%) which was observed in the experiment.

In general it may be concluded that large differences in behavior existed between the soybeans grown in the field and in pots. Although the P content of the leaves was raised somewhat by P application in the field this did not result in higher N content of the leaves, or yield responses. The reason that the percent N in the leaves was not raised may have been that nodulation and N content were already optimal. It must then be assumed that the roots accumulated sufficient P from the soil to meet the needs of the plant, by exploring an unlimited volume of soil. On the other hand the N content may have been high because another growth factor was limiting and perhaps the plant would have benefited from P application and increased nodulation if no other factor had been limiting and the N content had been diluted by faster growth. The comparison of critical P percentages suggests that high P contents at the end of flowering were not required for maximum yield in pots. At young stages the P content of the leaves was very high. It is unlikely that the expansion of root systems of plants was already restricted in the pots at the stage of two trifoliate leaves considering the size of the pots used. Reference to the contour maps for the percent P at this stage shows that plants which were to render maximum yield contained 0.75% P at this stage. Comparable data for the field experiments were not collected, but it may be presumed that the leaf contents were much lower than in the pots. At this time large responses in nodulation and green weight developed in the pots which were not matched under field conditions. Such strong differential development at early stages of development if they could be induced in the field may ultimately be reflected in yield responses.

Conclusions from the comparative behavior under field and pot conditions should not be extrapolated too far since several factors differed between the two types of experiments. The experiments were conducted with different varieties. The soybean lines introduced from the Far-East which were used in the pot trials may have differed in their ability to utilize absorbed nutrients. The field trials were dependent on rainfall whereas the pots were well supplied with water. The experiments were conducted with different soils. Plants grown in pots are further known to differ in nutrient uptake from those grown in the field due to a number of causes such as repeated drying and wetting of the soil, temperature changes in the pots, disturbance of the soil, etc. Also the strains of nodule bacteria in the root nodules could have been a factor. The pots were liberally treated with a slurry of commercial inoculant. This changed the distribution of seratypes in the nodules and made it practically independent of the range of fertilizers applied. The usual seratype (123) was largely replaced by three others present in the inoculant.[1] It is thought, however, that the imposed environment of a volume of uniformly fertilized soil in which the root systems were placed was the primary cause of the effects observed. This may have been accentuated at later stages by the unavoidable restriction of root systems

[1]Serological analyses were carried out by Dr. H. W. Johnson of the Crops Research Division, United States Department of Agriculture, Beltsville, now Head, Department of Agronomy and Plant Genetics, University of Minnesota, St. Paul.

in unfertilized pots to a limited volume of soil. Further work testing commercial varieties and introduced soybean lines side by side to compare their behavior will be necessary. This may best be performed in pot trials. Alternatively, the effects of placing young root systems in a highly fertilized soil environment may be studied by new fertilizer placement techniques in the field.

VI. SUMMARY

The primary objective of this research was to study means of obtaining large and consistent fertilizer responses in soybeans. One direction followed was aimed at establishing differential responses among unexplored numbers of introduced soybean lines. Other attempts involved simultaneous variation of three nutrient elements and higher rates of fertilization than had been applied in previous experimentation.

Field experiments were employed to compare the differential behavior of four commercial varieties. Pot trials were conducted to study the response of five soybean lines introduced from far-eastern countries to fertilization and to establish meaningful differential behavior among these lines. The five soybean introductions were selected from plantations of 355 and 48 lines during preliminary investigations on the basis of yield and leaf composition criteria.

Modified composite designs with three variables at 5 to 9 levels were used. Maximum rates of application of 400, 600 and 800 pp2m P were applied in various experiments. The highest rate of K application was 800 pp2m. That of Ca was either 2000 or 4000 pp2m. Experimental designs employed were randomized blocks and split-plot techniques. Observations included field symptoms, dry- and fresh-weight measurements of top and root growth at various stages of development, nodule counts and weight, chemical composition of the leaves and other plant parts with respect to P, K, Ca, Mg and N, yield of grain and soil test values.

Statistical analysis of the results followed well-known multiple

regression techniques. The data on yield of grain, number of nodules, nutrient contents of the leaves and any other variable of interest were fitted by quadratic polynomials usually comprised of 10 linear, quadratic and interaction terms referring to fertilizer input variables. The yield of grain and other dependent variables were also expressed as a function of leaf composition variables. Partial regression coefficients in the multiple regressions obtained for each variety were compared for differential effects by a statistical test on all corresponding coefficients simultaneously. If statistically justified the varietal multiple regression equations were subsequently combined into one equation maintaining individual varietal regression coefficients by means of dummy variables where significant differences existed among them. Such individual partial regression coefficients were later re-tested by a multiple range procedure. The results were interpreted from isoquant maps for the dependent variables. Critical nutrient percentages were computed where applicable.

On two soils in Iowa, testing low in P and K, significant yield responses to K application were obtained with four commercial varieties. At one location significant differential responses between varieties were found due to K. Responses to P were too weak to reach statistical significance despite low soil-P levels.

At one location significant differential responses to P application existed. Weak positive P responses occurred at rates of K exceeding practical application, but could explain some of the reputation of inconsistent fertilizer responses of soybeans. Residual effects of P and K fertilization were reduced after two years. That of liming increased several fold. The combination of fertilizers for maximum yield was located at very high levels of P and K. In one experiment all varieties required 500 to 550 lbs. of K and all but one (Chippewa) required more than 400 lbs. of P per acre for maximum yield. The variety Harosoy outyielded all other varieties. Its differences with Chippewa caused differential responses. The critical values for percent P, percent K and percent Ca were rather similar for all varieties. The chemical composition of the leaves except the percent N was significantly affected by fertilization. The percent P responded to P or P and K application. The P-sensitive variety Chippewa was found to have a significantly higher P content in the leaves at one location. The percent K was differentially affected by K application and sometimes by Ca. The percent Ca was increased by P and decreased by K application. The percent Mg was depressed by K fertilizer.

The P, K and N contents of the leaves changed significantly over a 9-day period at the end of flowering. The trend in percent P was generally downward. In the case of Harosoy the effect of K on the percent P changed significantly over this period. At one location and in one variety, Blackhawk, it was possible to revert the trend of K depletion from the leaves after the end of flowering temporarily by judicious choice of rate of K fertilization. This effect was practically independent of P fertilization. An opposite effect of K on the percent N in the leaves over the period just prior to the end of flowering was found in another variety, Harosoy. All differential responses in the field experiments tended to be of small magnitude. Leaf symptoms were found due to K deficiency.

In pot trials P toxicity symptoms developed at the time of unfolding of the third trifoliate leaf. Differences in tolerance of high P fertilization were found between introduced soybean lines. The most tolerant line showed weaker symptoms than others at equal rates of fertilization. Its P content of the leaves was not different at the stage of two trifoliate leaves but was considerably higher by the end of flowering. In all cases plants exhibiting P toxicity symptoms were larger than healthy plants not receiving P. It was found that high P levels in the soil stimulated the nodulation of the roots very strongly and was optimal at 550 pp2m P. The resulting increase in N supply to growing tissues increased the size of the diseased plants despite the reduction in effective photosynthetic area. The growth differences widened further with progressing development of the plant, while symptoms were alleviated. At the conclusion of the season several-fold increases in yield of soybeans were recorded under optimum conditions. It is thought that the uniform distribution of high P fertility in the root environment of the pots played a major role in the growth benefits at young stages. At later stages the restriction of root expansion of plants not receiving P treatments possibly accentuated the responses. Apart from significant responses to P, the plants also responded to K application although the soil was not low in K. Differential responses to P and the PCa interaction were significant and large. Seed size was influenced by the same factors and the number of significant differential effects recorded was even larger for seed size than for the yield of soybeans. Pot and field trials agreed in estimates of very high fertilizer requirements for maximum yield. Approximately 500 pp2m P, 660 pp2m K and 4000 pp2m Ca led to maximum yield in pot culture.

Dry and fresh weights of plant tops and roots responded strongly to P application and in various cases to K and the PK or PCa interaction. Differential responses to P, PK and PCa were highly significant at the end of flowering, but less pronounced at the stage of seven trifoliate leaves and of no practical consequence at the two-leafed stage. It was found that differential effects were not necessarily in favor of the same line at all stages of growth. It therefore is to be expected that some may overtake others in rate of growth with time. The line producing the least green weight at early stages formed the largest plants by the end of flowering and produced the highest yield at any point in the investigated region of P and K application. The P, P^2 and PCa-interaction effects were of the greatest significance for the number and weight of nodules. Highly significant varietal differences existed and differential responses of nodule-weight to P were significant and substantial. A three-fold rise in weight of nodules was predicted at a certain combination of fertilizers in one experiment. Another experiment predicted a 22-fold rise in number and a 10-fold rise in weight of nodules as maximum response to fertilization. Stem weight benefited most from the associated increase in N-fixation and roots the least. The plant parts were tentatively placed in the following order of decreasing benefit:

$$\text{stems} > \text{petioles} > \text{leaves} > \text{roots}.$$

During the period from the seven-leafed stage to the end of flowering the number of nodules on the roots of the plant was doubled and their weight more than tripled. It was found that the fertilization for maximum nodulation, green matter production and yield were closely related.

The composition of the leaves was strongly affected by fertilization. The percent P was mainly affected by P, Ca, PK and PCa. The percent K was primarily affected by K, Ca and KCa, sometimes also by P and PK. The percentages Ca and Mg were influenced by most fertilizer variables. The main factor affecting the percent N was P. Differential responses of the percent P and percent N were pronounced at the end of flowering, but none reached practical dimensions at early stages of development. The predicted range of nutrient contents of the leaves over the region of fertilization was wide for the percentages P, K and N. That for the percent N widened and those for percent P and percent K narrowed with increasing stage of development. The chemical composition of the roots was affected similarly to that of the leaves. The importance of the N supply for yield was indicated in one pot trial by the fact that the maximum yield of soybeans occurred at that fertilizer combination which also resulted in the maximum percent N in the leaves at the end of flowering. Regression equations expressing yield or dry-matter production as a function of leaf composition variables involving values for five nutrients were found unsatisfactory due to, presumably, interdependence of these variables. Critical nutrient percentages were therefore estimated by substitution of fertilizer levels at maximum yield into the regression equations expressing the percentage of each individual nutrient as a function of fertilizer input variables. Critical nutrient percentages for the yield of soybeans in pots, expressed as leaf contents at the end of flowering, were rather comparable to those obtained from field experiments. One line, Entry 1, showed a higher value for the percent P than the others. Differential behavior of introduced soybean lines to fertilization was clearly established. It is likely however, that desirable properties will be distributed over a number of lines and that detailed study will be required to identify lines which are superior in some characteristic or responsiveness.

Since the marked growth responses described in this dissertation referred to introduced soybean lines it may be desirable to compare the responses of existing varieties with those of the introduced lines in pot studies. And since the principal difference between pot and field responses appears to lie in stimulation of growth in the early stages of development future investigations may be designed to obtain similar responses in the field by employing new techniques of fertilizer placement whereby young root systems are surrounded by highly fertilized soil in which the fertilizers are uniformly distributed.

VII. LITERATURE CITED

Anderson, R. L. and Bancroft, T. A. 1952. Statistical theory in research. New York, N. Y. McGraw-Hill Book Co., Inc.

Barnard, A. J., Jr., Broad, W. C. and Flaschka, H. 1956. The EDTA titration: Nature and methods of end point detection: I. Chemist-Analyst 45: 86-93, 111-112.

Beckenbach, J. R., Robbins, W. R. and Shive, J. W. 1938. Nutrition studies with corn: II. A statistical interpretation of the relation between the ionic concentration of the culture solutions and the element content of the tissue. Soil Sci. 45: 403-426.

Bennett, J. P. 1945. Iron in leaves. Soil Sci. 60: 91-105.

Box, G. E. P. and Wilson, K. B. 1951. On the experimental attainment of optimum conditions. Roy. Stat. Soc. J. Series B, 13: 1-45.

Brown, J. C., Tiffin, L. O., Holmes, R. S., Specht, A. W. and Resnicky, J. W. 1959. Internal inactivation of iron in soybeans as affected by root growth medium. Soil Sci. 87: 89-94.

Dumenil, L. C. 1961. Nitrogen and phosphorus composition of corn leaves and corn yields in relation to critical levels and nutrient balance. Soil Sci. Soc. Amer. Proc. 25: 295-298.

Duncan, D. B. 1945. Multiple range and multiple F tests. Biometrics 11: 1-42.

Fletcher, H. F. 1961. Differential effects of phosphorus fertility on soybean varieties. Unpublished Ph.D. thesis. Urbana, Illinois, Library, University of Illinois.

Fletcher, H. F. and Kurtz, L. T. 1964. Differential effects of phosphorus fertility on soybean varieties. Soil Sci. Soc. Amer. Proc. 28: 225-228.

Foote, B. D. and Howell, R. W. 1964. Phosphorus tolerance and sensitivity of soybeans as related to uptake and translocation. Plant Physiology 39: 610-613.

Fuller, W. A. 1962. Estimating the reliability of quantities derived from empirical production functions. Farm Econ. J. 49: 82-99.

Hammond, L. C., Black, A. C. and Norman, A. G. 1951. Nutrient uptake by soybeans on two Iowa soils. Iowa State Coll. Agr. Expt. Sta. Res. Bul. 384: 463-512.

Hanway, J. J. 1962. Corn growth and composition in relation to soil fertility: II. Uptake of N, P and K and their distribution in different plant parts during the growing season. Agron. J. 54: 217-222.

Hanway, J. J. and Heidel, H. 1952. Soil analysis methods as used in the Iowa State College Soil Testing Laboratory. Agron. 57 (Rev.) (Mimeo.) Ames, Iowa, Iowa Agr. Expt. Sta.

Heady, E. O., Pesek, J. T. and Brown, W. G. 1955. Crop response surfaces and economic optima in fertilizer use. Iowa Agr. Expt. Sta. Res. Bul. 424.

Howell, R. W. and Bernard, R. L. 1962. Phosphorus response of soybean varieties. Crop Science 1: 311-313.

Howell, R. W. and Cartter, J. L. 1958. Physiological factors affecting composition of soybeans: II. Response of oil and other constituents of soybeans to temperature under controlled conditions. Agron. J. 50: 664-667.

Jones, J. B., Jr. 1960. Nutrient element requirements for several inbred lines of corn. Soil Science Congress, 7th, Madison, Wisconsin, 1960. Intern. Transactions 3: 336-342.

Macy, P. 1936. The quantitative mineral nutrient requirements of plants. Plant Physiology 11: 749-764.

Miller, R. J. 1960. Soybean yield responses and plant composition as affected by phosphorus and potassium fertilizers. Unpublished Ph.D. thesis. Ames, Iowa, Library, Iowa State University of Science and Technology.

Miller, R. J., Pesek, J. T., Hanway, J. J. and Dumenil, L. C. 1964. Soybean yields and plant composition as affected by phosphorus and potassium fertilizers. Iowa Agr. and Home Ec. Expt. Sta. Res. Bul. 524.

Morris, H. D. and Pierre, W. H. 1949. Minimum concentrations of Manganese necessary for injury to various legumes in culture solutions. Agron. J. 41: 107-112.

Nelson, W. L., Burkhart, L. and Colwell, W. E. 1945. Fruit development, seed quality, chemical composition and yield of soybeans as affected by potassium and magnesium. Soil Sci. Soc. Amer. Proc. 10: 224-229.

Ohlrogge, A. J. 1960. Mineral nutrition of soybeans. Adv. Agron. 12: 229-263.

Snedecor. G. W. 1956. Statistical methods. 5th ed. Ames, Iowa. Iowa State University Press.

Snider, H. J. 1943. Manganese in some Illinois soils and crops. Soil Sci. 56: 187-195.

Sutton, Paul. 1962. Relationships among seven elements in the nutrition of corn in sand culture. Unpublished Ph.D. thesis. Ames, Iowa, Library, Iowa State University of Science and Technology.

Tucker, B. M. 1957. Calcein as an indicator for the titration of Calcium with ethylenediaminetetra-acetate. Analyst 82: 284-285.

Tyner, E. H. 1946. The relation of corn yields to leaf nitrogen, phosphorus and potassium content. Soil Sci. Soc. Amer. Proc. 11: 317-323.

Viets, F. G., Jr., Boawn, L. C. and Crawford, C. L. 1954. Zinc contents and deficiency symptoms of 26 crops grown on a Zinc-deficient soil. Soil Sci. 78: 305-316.

Ward, G. H. and Johnston, F. B. 1960. Chemical methods of plant analysis. Publication 1064, Canada Dept. Agr., Research Branch, Ottawa, Ontario.

Waring, S. A. and Bremner, J. M. 1964. Ammonium production in soil under waterlogged conditions as an index of nitrogen availability. Nature 201, No. 4922: 951-952.

Williams, E. J. 1959. Regression analysis. New York, N. Y. John Wiley and Sons, Inc.

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IX. APPENDIX

The general formula for the F-ratio testing a set of corresponding partial regression coefficients from multiple regression equations with identical terms given by Williams (1959) is

$$F = \frac{\sum_r \frac{b_{ri}^{2}}{t_r^{ii}} - \bar{b}_i^{2} \sum_r \frac{1}{t_r^{ii}}}{(m-1)s_c^{2}}$$

or:

$$F = \frac{\sum_r \frac{(b_{ri} - \bar{b}_i)^2}{t_r^{ii}}}{(m-1)s_c^{2}}$$

where

$r = 1, \ldots, m$ denotes the number of sets of partial regression coefficients,

$t_r^{ii} = c_{ii}$ of the rth set.

s_c^{2} = combined residual mean square.

In the special case where

$m = 2$ and $t_1^{ii} = t_2^{ii} = c_{ii}$ and replacing

s_c^{2} b s_e^{2}, the equation simplifies to

$$F = \frac{(b_{1i} - \bar{b}_i)^2 + (b_{2i} - \bar{b}i)^2}{\cdot\ c_{ii}\ s_e^2\ .} =$$

$$F = \frac{(b_{1i} - \frac{b_{1i} + b_{2i}}{2})^2 + (b_{2i} - \frac{b_{1i} + b_{2i}}{2})^2}{c_{ii} \cdot s_e^2} =$$

$$F = \frac{b_{1i}^2 + \frac{b_{1i}^2 + b_{2i}^2 + 2b_{1i}b_{2i}}{4} - b_{1i}^2 - b_{1i}b_{2i} + b_{2i}^2 +}{c_{ii} \cdot s_e^2}$$

$$+ \frac{\frac{b_{1i}^2 + b_{2i}^2 + 2b_{1i}b_{2i}}{4} - b_{1i}b_{2i} - b_{2i}^2}{c_{ii} \cdot s_e^2} =$$

$$F = \frac{(b_{1i} - b_{2i})^2}{2\ c_{ii} \cdot s_e^2}$$

Since $t^2 = F$ at 1 and n degrees of freedom this reduces to

$$t = \frac{b_{1i} - b_{2i}}{\sqrt{c_{ii} \cdot s_e^2 \cdot 2}}$$

Table 127. Elements of the inverse matrix for the experimental design used for the pot experiments after correction for the Ca contained in concentrated superphosphate

Elements					
	c_{11}	c_{12}	c_{13}	c_{14}	c_{15}
c_{11}	0.258599	-0.026312	-0.057749	-0.047249	0.014245
c_{21}		0.241952	-0.033647	0.016258	-0.046446
c_{31}			0.240726	0.016271	0.016046
c_{41}				0.011558	-0.004064
c_{51}					0.011612
	c_{16}	c_{17}	c_{18}	c_{19}	$c_{1\ 10}$
c_{11}	0.021281	-0.016936	-0.019852	-0.007702	0.004265
c_{21}	0.016053	-0.015334	-0.011537	-0.015268	0.003959
c_{31}	-0.046418	-0.007702	-0.004565	-0.015021	0.003834
c_{41}	-0.003866	0.000000	0.000458	0.000000	0.000000
c_{51}	-0.004013	0.000000	0.000905	0.000000	0.000000
c_{61}	0.011611	0.000000	-0.002615	0.000000	0.000000
c_{71}		0.008468	0.004265	0.003851	-0.002132
c_{81}			0.008099	0.003834	-0.001917
c_{91}				0.007510	-0.001917
$c_{10\ 1}$					0.000958

Table 128. Elements of the inverse matrix for the experimental design used for the field trial located at the Howard County Experimental Farm after correction for the Ca contained in concentrated superphosphate

	Elements				
	c_{11}	c_{12}	c_{13}	c_{14}	c_{15}
c_{11}	0.064874	-0.007295	-0.017270	-0.005765	0.001875
c_{21}		0.059008	-0.009831	0.002231	-0.005626
c_{31}			0.058640	0.002202	0.002186
c_{41}				0.000697	-0.000279
c_{51}					0.000703
	c_{16}	c_{17}	c_{18}	c_{19}	$c_{1\ 10}$
c_{11}	0.002988	-0.002182	-0.000961	-0.002729	0.000273
c_{21}	0.002187	-0.001927	-0.001915	-0.001622	0.000250
c_{31}	-0.005625	-0.000961	-0.001872	-0.000269	0.000239
c_{41}	-0.000259	0.000000	0.000000	0.000041	0.000000
c_{51}	-0.000273	0.000000	0.000000	0.000078	0.000000
c_{61}	0.000703	0.000000	0.000000	-0.000200	0.000000
c_{71}		0.000545	0.000240	0.000273	-0.000068
c_{81}			0.000468	0.000239	-0.000060
c_{91}				0.000525	0.000060
$c_{10\ 1}$					0.000015

Table 129. Elements of the inverse matrix for the experimental design used for the field trial at the Carrington-Clyde Experimental Farm

	Elements				
	c_{11}	c_{12}	c_{13}	c_{14}	c_{15}
c_{11}	0.048735	-0.002474	-0.004710	0.001225	-0.001832
c_{21}		0.048735	0.001225	-0.004710	-0.001832
c_{31}			0.000589	-0.000153	0.000000
c_{41}				0.000589	0.000000
c_{51}					0.000458